Setting up of Optimum Design Parameters for Agrivoltaic Power Plants in Indian Geo-Climatic Conditions

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ABSTRACT

Agrivoltaics is a promising solution for addressing the growing demand for food and energy in the face of climate change, land scarcity, and rising populations. This comprehensive study aims to establish design parameters for agrivoltaic power plants across various geo-climatic regions and soil types in India. The study explores India's major geo-climatic regions and soil types, examining the multiple crops cultivated in these regions and identifying plant characteristics critical for agrivoltaics, such as plant physiology, root penetration, growth pattern, sunlight requirement (Photosynthetically Active Radiation) and Daily Light Integral (DLI) values, plant life, and sowing and harvesting seasons. The research develops a methodological framework and matrix for determining suitable crops for agrivoltaic systems in different geo-climatic regions and soil types.

The research establishes design and installation parameters for agrivoltaic setups, considering geographical and climate conditions, PV modules layout and structure design considering sunlight requirement of plants, foundation type, selection and matching of equipment, cable layout design, system protection requirements, energy yield estimation, installation, operation, and maintenance requirements. Moreover, the study explores the cost impact of various design aspects on agrivoltaic economics, providing valuable insights for stakeholders looking to invest in agrivoltaic power plants. By understanding the influence of design parameters on the overall cost, stakeholders can make informed decisions and optimise the development of agrivoltaic systems.

One of the critical outcomes of this study is the development of a method and matrix to determine the amount of sunlight available in different zones within a solar field segment for different structural configurations in terms of inter-row spacing, height, width and tilt angle. By knowing the available sunlight in different zones during different seasons of the year, appropriate crops/ plants can be selected to grow under these zones based on the minimum sunlight required to produce such plants. The System Advisory Model developed by the National Renewable Energy Laboratory was used to simulate the results in multiple scenarios.

Keywords: Agrivoltaics, photovoltaics, photosynthetically active radiation, daily light integral

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List of Abbreviations

Abbreviation	**Description**
APV	Agri-Photovoltaics
CUF	Capacity Utilization Factor
DLI	Daily Light Integral
GHI	Global Horizontal Irradiance
HDGI	Hot Dipped Galvanized Iron
ICAR	Indian Council of Agricultural Research
IEC	International Electrotechnical Commission
IP	Ingress Protection

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IS	Indian Standards
NREL	National Renewable Energy Laboratory
NSRDB	National Solar Radiation Database
O&M	Operation and Maintenance
PAR	Photosynthetically Active Radiation
PR	Performance Ratio
PV	Photo-Voltaic
SAM	System Advisory Model

List of Units

Units	Description
%	Percentage
^{o}	Degree
^{o}C	Celsius
km	Kilometre
km/hr	Kilometre per hour
kV	Kilovolt
kW	Kilowatt
kWh	Kilowatt Hour
kW_p	Kilo Watt peak
m/s	Meter per second
MW	Megawatt
MW_p	Megawatt peak
W	Watt
W_p	Watt peak

1 Introduction

Renewable energy technologies are crucial in addressing the global need for sustainable energy and environmental conservation. India, a prominent player in this global transition, is undergoing significant changes in its energy landscape. The nation actively diversifies from its traditional, centralised coal-hydro energy supply towards a broader portfolio of renewable energy (RE) sources. As of 2022, India held the 4th position worldwide in total renewable power capacity [1][2][3]. By May 2023, renewable power, including large hydropower, comprised 41.57% of India's total energy capacity, an equivalent of 173.61 GW out of 417.67 GW [4][5]. However, excluding large hydropower, the renewable power capacity accounted for 30.35%, amounting to 126.77 GW of the total renewable energy capacity [4,5]. This progress was spurred by India's ambitious targets to install 175 GW and 450 GW of renewable energy by 2022 and 2030, respectively [6][7].

Agrivoltaics or Agrovoltaics, also known as Agro-photovoltaics, refers to the innovative integration of solar photovoltaic systems and agriculture, which allows for the simultaneous production of food and renewable energy. This approach is significant as it can increase land use efficiency, increase crop yields, and improve the performance of solar panels by providing a cooler microclimate. Notable progress in this field has been made worldwide, with numerous projects and research studies conducted to understand and optimise the combination of solar energy systems and agriculture. In India, agrivoltaics has gained traction as a promising solution to meet the growing demand for food and energy, especially considering the country's vast agricultural land and abundant solar potential.

The critical issue is the delicate balance between land use for food production and energy generation –the food-energy nexus. The concept of agrivoltaics offers a promising solution. Agrivoltaics integrates agricultural practices with solar power production, enabling simultaneous crop growth and solar energy generation on the same plot of land. This synergistic approach could optimise land utilisation, benefiting farmers by enhancing crop growth conditions and offering an additional source of income. While the execution of agrivoltaics demands thoughtful planning to meet agricultural and energy generation needs effectively, it bears substantial potential to boost India's renewable energy capacity without endangering food supplies [8][9][10][11].

With abundant sunlight, expansive agricultural land, and a rapidly growing solar PV sector, India is an ideal candidate for implementing agrivoltaics. However, the nation's diverse geo-climatic conditions and variety of soil types present unique challenges in designing agrivoltaic power plants that can accommodate different crops and optimise energy production. Although still in its nascent stage, India has seen a growing number of agrivoltaic pilot projects in recent years. The National Solar Energy Federation of India (NSEFI), in association with the Indo-German Energy Forum (IGEF), has conducted a study on the current ongoing agrivoltaic projects in India, identifying 21 projects spread across the country [12]. These diverse projects, located in various geographic and socioeconomic contexts, highlight the significant potential of agrivoltaics in advancing India's renewable energy objectives and simultaneously offering substantial advantages to local agriculture. This highlights the necessity for a comprehensive study of the design parameters of agrivoltaic power plants suitable for various regions across India.

India's extensive geographic and climatic diversity contributes to various geo-climatic regions and soil types, each with unique agricultural attributes. Recognising this complexity, the Planning Commission of India, in association with the National Remote Sensing Agency, divided the country into 15 Agro-climatic regions [13]. They stretch from the Western Himalayan Region to the Islands Region, covering all states and union territories, and offering unique agricultural challenges and opportunities. A comprehensive understanding of the interrelation between these geo-climatic zones, soil types, and cultivated crops was established using many resources [14][15]. These resources provided a detailed delineation of India's 15 Agro-climatic zones, soil types, temperature ranges, rainfall, and major crops cultivated in each zone. They also offered an agricultural contingency plan outlining the agricultural profile of each zone.

This paper aims to thoroughly analyse these design parameters in differing geo-climatic and soil conditions. By investigating the factors influencing the design, construction, and operation of agrivoltaic systems, this study aims to identify suitable crop types and best practices for effective agrivoltaic project implementation in India. It is expected that the outcomes of the study will provide valuable insights and guidelines for developing agrivoltaic projects in India with a better understanding of technical design aspects.

The introductory section of this paper provides the growth scenario of solar PV in India and the study's objective. The second section offers critical plant characteristics in terms of height, sunlight requirement, root penetration, plant life and cultivation time and method of sowing and harvesting. The third section discusses agrivoltaic design considerations, which cover the design of the mounting structure, plant layout, and selection of crops based on structure heights and available sunlight. The matrices for selecting crops for different agrivoltaic setups in other geo-climatic regions of India have been presented in this section. The fourth section of this paper offers the aspects of system performance and the cost impact of different design aspects. The conclusion of the study is included in section 5.

2 Critical characteristics of crops for agrivoltaic

2.1 Height

The height of crops is one of the most critical factors for agrivoltaic setup. When crops are cultivated in an agrivoltaic setup, solar panels should not obstruct their growth, and they should not cast any shadow on the solar panels. Cultivated crops should be able to grow well in the space beneath and between the solar arrays/panels, and any possibility of damaging solar modules during sowing and harvesting time should be taken into consideration. It is equally crucial that crops grown in front of the solar arrays should not cast any shadow between 9 a.m. and 4 p.m. (This time should be adjusted based on solar time). Table 1 below provides a classification of typical crops cultivated in India based on typical maximum height [16][17].

Table 1: Classification of crops based on the typical maximum height

Typical maximum height	Typical crops
Less than 50 cm	Herbs: Gucchi (Himalayan Mushroom), Sugar Beet, Carrot, Radish, Cabbage, Cauliflower, Spinach, Black Gram, Sankhpuspi, Groundnut, Lettuce, Cumin, Isabgol etc. Creepers: Watermelon, Zucchini, pumpkin, Ash gourd etc.
Less than 100 cm	Herbs: Aloe vera, Mustard, Ginger, Green Gram, Mungbean, Onion, Kariyatu (Andrographis paniculata), Cow Pea, Parsley, Poppy, Stevia Leaves, Rye, Oats, Chick Pea (Gram or Bengal gram), Mothbean, Cluster Bean, Fenugreek, Mari Gold, Mint Leaves, Brinjal (eggplant), Capsicum, Chilli, Geranium, Coriander, Garlic etc. Shrubs: Tea, Patchouli, Sarpagandha, Berseem Clover, Potato etc.
Less than 150 cm	Herbs: Arrowroot, Asparagus, Soybean, Turmeric, Ashwagandha, Rice, Linseed, Wheat, Elephant Foot (Yam), Tomato etc. Shrubs: Jethimadh, Tobacco etc.
Less than 200 cm	Herbs: Cotton, Fennel, Sesame, Indigo, Maize etc. Shrubs: Raspberry, Senna etc. Climber (controlled): Betel Leaves, Black Pepper, Indian Bean, Long bean, French Bean, Ash gourd (Pusa Urmi), Snake Gourd, Bitter gourd, Bottle Gourd, Blonde cucumber etc. Grass: Citronella, Vetiver etc.
Less than 300 cm	Herbs: Ladies Finger (Okra) Shrubs: Sonamukhi, Pearl millet (Bajra), Guava Hybrid etc. Grass: Hybrid Napier Grass, Lemon Grass etc.
More than 300 cm	Herbs: Banana, Cardamom, Jute etc. Shrubs: Coffee, Castor, Annatto dye, Sunn Hemp etc. Grass: Guinea Grass, Sugarcane etc. Trees: Papaya, Pomegranate, Kiwi, Mango, Pigeon Pea, Sapota (Chiku) etc.

2.2 Sunlight Requirement

All crops need sunlight for photosynthesis, but the amount required can vary significantly. Some crops require full sun, while others can tolerate or even prefer partial shade. In an agrivoltaic system, solar panels can create shaded areas, which can be beneficial for shade-tolerant crops but detrimental for those needing full sun. Table 5 below categorises the crops into four groups based on their DLI requirements: low light (3-6 $mol{\cdot}m^{-2}{\cdot}day^{-1}$), medium light (6-12 $mol{\cdot}m^{-2}{\cdot}day^{-1}$), high light (12-18 $mol{\cdot}m^{-2}{\cdot}day^{-1}$), and very high light (exceeding 18 $mol{\cdot}m^{-2}{\cdot}day^{-1}$) crops **Error! Reference source not found.Error! Reference source not found.**.

Table 2: Classification of crops based on sunlight requirement

Typical sunlight requirement	Typical crops
Low light crops Daily light integral (DLI): 3 to 6 (mol/m²/day) Solar Radiation: 0.41 to 0.83 kWh/m^2/day	Herbs: Centella asiatica (Brahmi Booti/ Mandukaparni), Himalayan Mushroom (Gucchi), Arrowroot
Medium-light crops Daily light integral (DLI): 6 to 12 (mol/m²/day) Solar Radiation: 0.83 to 1.66 kWh/m^2/day	Herbs: Carrot, Cauliflower, Mustard, Parsley, Cow Pea, Radish, Mungbean, Green Gram, Parsley, Cow Pea, Cotton, Vetiver, Okra/ Ladies finger/ Bhindi, Sugar beet, Ginger, Aloe vera, Kariyatu (Andrographis paniculata), Poppy, Asparagus, Soybean, Turmeric, Aswagandha, Cotton, Fennel, Asparagus, Soybean, Turmeric, Jute Shrubs: Peas, Sonamukhi, Sarpagandha, Tea, Patchouli, Jethimadh, Cardamom, Climbers: Black Pepper (climber), Betel Leaves Grass: Guinea Grass, Citronella, Vetiver (grass) Tree: Papaya
High light crops Daily light integral (DLI): 12 to 18 (mol/m²/day) Solar Radiation: 1.66 to 2.48 kWh/m^2/day	Herbs: Black Gram, Cabbage, lettuce, Spinach, Onion, Coriander, Rye, Fenugreek, Garlic, Mint, Wheat, Lettuce, Spinach, Onion, Chilli, Eggplant, Stevia Leaves, Coriander, Garlic, Rye, Sesame, Chicory, Sankhpuspi, Groundnut, Isabgol, Cumin, Stevia Leaves, Oats, Chick Pea, Moth bean, Cluster Bean, Fenugreek, Marigold, Mint Leaves Chicory (herb), Brinjal, Capsicum, Elephant foot yam, Linseed, Tomato, Raspberry, Senna, Indigo Shrubs: Potato, Tobacco, Pearl millet (Bajra), Guava Hybrid, Berseem Clover, Senna, Sunn Hemp, Annatto dye, Castor Creeper: Ash gourd Climbers: Snake Gourd, Bitter gourd, Indian Bean, Ash gourd, Long bean, French Bean, Grass: Sugar Cane Tree: Pigeon Pea, Kiwi, Mango, Pigeon pea
Very high-light crops Daily light integral (DLI): More than 18 (mol/m²/day) Solar Radiation: More than 2.48 kWh/m^2/day	Herbs: Paddy Rice, Maize, Poppy, Geranium Creepers: Pumpkin, Watermelon, Zucchini Climber: Bottle Gourd, Blonde cucumber

2.3 Root Penetration

The depth and spread of a plant's roots can significantly impact agrivoltaic systems. Crops with deep root systems may not be suitable if underground cables and other infrastructure are present. Moreover, root systems also affect soil erosion and water uptake, which can have implications for the maintenance and efficiency of agrivoltaic systems [16][17].

Table 3: Classification of crops based on root penetration

Typical root depth and spread	Typical crops
Root depth: Less than 50 cm Root spread: Less than 100 cm	Herbs: Centella asiatica (Brahmi Booti/ Mandukaparni), Gucchi (Himalayan Mushroom), Arrowroot, Aloe vera, Ginger, Radish, Fenugreek, Cumin, Mint Leaves, Capsicum, Geranium, Garlic etc. Shrubs: Patchouli, Potato Climber: Betel Leaves
Root depth: Less than 100 cm Root spread: Less than 100 cm	Herbs: Mustard, Green Gram, Mungbean, Kariyatu (Andrographis paniculata), Soybean, Turmeric, Aswagandha, Fennel, Parsley, Sesame, Spinach, Stevia Leaves, Rye, Linseed, Wheat, Indigo, Mari Gold, Brinjal (eggplant), Chilli, Maize Shrubs: Tea, Jethimadh, Peas, Berseem Clover, Raspberry, Tobacco Grass: Citronella grass, Hybrid Napier Grass Climber: Black Pepper, Indian Bean, Long bean, French Bean, Snake Gourd, Bitter gourd, Blonde cucumber, Ash gourd, Bottle Gourd, Creeper: Ash gourd
Root depth: Less than 150 cm Root spread: Less than 100 cm	Herbs: Cow Pea, Cotton, Jute, Chick Pea (Gram or Bengal gram), Cluster Bean, Chicory Shrubs: Sonamukhi, Castor, Sunn Hemp etc. Grass: Vetiver
Root depth: Less than 150 cm Root spread: More than 100 cm	Herb: Banana, Asparagus, Cardamom, Elephant Foot (Yam) Shrubs: Coffee, Senna, Annatto dye, Guava Hybrid Grass: Guinea Grass, Sugarcane Creepers: Pumpkin, Watermelon, Zucchini Tree: Kiwi, Papaya, Pigeon Pea, Sapota (Chiku), Mango,

2.4 Crop life and growing season

The lifespan of the crops and how that aligns with the solar panel lifecycle is another factor to consider. Perennial crops that don't require yearly replanting could benefit an agrivoltaic system. The cropping system (annual or perennial) will influence the design of the agrivoltaic system in terms of panel height, orientation, and arrangement [16][17].

Table 4: Classification of crops based on life cycle

Plant Life	Typical crops
Annual (crops which completes their life cycle within one growing season)	Herbs: Sugar Beet, Mustard, Green Gram, Radish, Mungbean, Kariyatu (Andrographis paniculata), Soybean, Cauliflower, Cow Pea, Cotton, Jute, Lady Finger (Okra), Poppy, Paddy Rice, Sesame, Cabbage, Black Gram, Oats, Chick Pea (Gram or Bengal gram), Linseed, Wheat, Groundnut, Mothbean, Cluster Bean, Fenugreek, Lettuce, Cumin, Isabgol, Mari Gold, Mint Leaves, Tomato, Chilli, Coriander, Garlic, Maize Shrubs: Peas, Berseem Clover, Pearl millet (Bajra), Sunn Hemp, Tobacco Creeper: Watermelon, Zucchini, Pumpkin, Ash gourd Climber: Long bean, French Bean, Ash gourd, Snake Gourd, Bitter gourd, Bottle Gourd, Blonde cucumber
Biennial	Herbs: Carrot, Parsley, Onion, Rye, Indigo

(crops which complete their life cycle in two years)	
Perennial (crops that live for more than two years)	Herbs: Centella asiatica (Brahmi Booti/ Mandukaparni), Gucchi (Himalayan Mushroom), Banana, Arrowroot, Aloe vera, Ginger, Asparagus, Turmeric, Ashwagandha, Cardamom, Fennel, Spinach, Stevia Leaves, Sankhpuspi, Chicory, Elephant Foot (Yam), Brinjal (eggplant), Capsicum, Geranium Shrubs: Coffee, Tea, Patchouli, Sarpagandha, Jethimadh, Sonamukhi, Raspberry, Senna, Castor, Annatto dye, Guava Hybrid, Potato Grass: Guinea Grass, Hybrid Napier Grass, Lemon Grass, Vetiver, Citronella grass, Sugarcane Climbers: Betel leaves, Black pepper, Indian bean Trees: Papaya, Pomegranate, Kiwi, Mango, Pigeon Pea, Sapota (Chiku)

2.5 Method of sowing and harvesting

Sowing and harvesting methods and the tools and equipment used are to be considered in designing agrivoltaic systems. The method of sowing and harvesting and the types of tools and equipment used in these processes are essential to understand to assess if any specific design considerations are required for agrivoltaic systems.

Impact of sowing methods on agrivoltaic design

For methods such as transplanting, agrivoltaic structures should facilitate easy access for workers, necessitating wider pathways between solar panels. Broadcasting demands even panel spacing, with the potential for movable setups to ensure uniform light distribution across the field. The dibbling technique requires the design to be non-obstructive, ensuring precision in seed placement and adequate sunlight penetration. Meanwhile, the drilling method stresses the importance of solar panel alignment to prevent shadowing on the sown rows and provide ample space for the operation and movement of drilling equipment.

Tale 8 below presents sowing methods of different crops cultivated in India [18][19][20][21][22][23][24][25].

Table 5: Classification of crops based on the method of sowing

Method of sowing	Typical crops
Transplanting	Herbs: Centella asiatica (Brahmi Booti/ Mandukaparni), Banana, Arrowroot, Aloe vera, Sugar Beet, Asparagus, Kariyatu (Andrographis paniculata), Aswagandha, Cardamom, Parsley, Onion, Stevia Leaves, Lettuce, Mint Leaves, Elephant Foot (Yam), Brinjal (eggplant), Tomato, Chilli, Geranium Shrubs: Coffee, Tea, Patchouli, Sarpagandha, Jethimadh, Raspberry, Annatto dye, Guava Hybrid, Tobacco Climber: Betel Leaves, Black Pepper Trees: Papaya, Pomegranate, Kiwi, Mango, Sapota (Chiku) Grass: Guinea grass, Lemon grass, Sugarcane
Broadcasting	Herbs: Green Gram, Radish, Fennel, Jute, Poppy, Rice, Sesame, Spinach, Black Gram, Rye, Linseed, Wheat, Indigo, Sankhpuspi, Cluster Bean, Fenugreek, Cumin, Isabgol, Mari Gold, Chicory Shrubs: Sonamukhi, Berseem Clover, Senna, Sunn Hemp Grass: Hybrid Napier Grass, Vetiver
Dibbling	Herbs: Carrot, Ginger, Mung bean, Soybean, Turmeric, Cauliflower, Cotton, Lady Finger (Okra), Cabbage, Chick Pea (Gram or Bengal gram), Capsicum, Coriander, Maize Shrubs: Pearl millet (Bajra), Castor

Method of sowing	Typical crops
	Creeper: Watermelon, Zucchini Climber: Indian Bean, Long bean, French Bean, Snake Gourd, Bitter gourd, Bottle Gourd, Blonde cucumber Tree: Pigeon pea
Drilling	Herbs: Mustard, Cow Pea, Oats, Groundnut, Moth bean, Garlic Shrubs: Peas, Potato Creeper/ Climber: Pumpkin, Ash gourd

Impact of harvesting methods on agrivoltaic design

Harvesting by hand emphasises the need for an agrivoltaic design that supports the free movement of workers around panel structures. When harvesting with hand tools, the design must provide adequate space between the panels to prevent any accidental damage during the use of tools. In contrast, machine harvesting demands a design with even more spacious setups to accommodate large machinery. The structures must also be robust and possibly elevated, ensuring they can withstand potential contact with the machines and provide the necessary clearance.

Tale 6 below presents harvesting methods of different crops cultivated in India [18][19][20][21][22][23][24][25].

Table 6: Classification of crops based on the method of harvesting

Method of harvesting	Typical crops
Harvesting by hand	Herbs: Cardamom, Cow Pea, Cotton, Onion, Cluster Bean, Lettuce, Isabgol, Mari Gold, Chicory, Tomato, Capsicum, Chilli, Coriander, Garlic Shrubs: Tea, Patchouli, Sonamukhi, Peas, Raspberry, Annatto dye, Guava Hybrid Creeper: Ash gourd Climber: Betel Leaves, Black Pepper, French Bean, Ash gourd, Bitter gourd, Bottle Gourd, Cucumber Trees: Papaya, Pomegranate, Kiwi, Mango, Sapota (Chiku)
Harvesting with hand tools	Herbs: Centella asiatica (Brahmi Booti/ Mandukaparni), Gucchi (Himalayan Mushroom), Banana, Arrowroot, Aloe vera, Carrot, Mung bean, Asparagus, Kariyatu (Andrographis paniculata), Soybean, Cauliflower, Fennel, Jute, Lady Finger (Okra), Parsley, Poppy, Rice, Sesame, Cabbage, Spinach, Black Gram, Stevia Leaves, Rye, Oats, Chick Pea (Gram or Bengal gram), Linseed, Wheat, Indigo, Sankhpuspi, Moth bean, Fenugreek, Mint Leaves, Elephant Foot (Yam), Brinjal (eggplant), Geranium, Maize Shrubs: Coffee, Sarpagandha, Berseem Clover, Senna, Pearl millet (Bajra), Castor, Sunn Hemp, Tobacco Climbers: Indian bean, Long bean, Snake gourd Grass: Hybrid Napier Grass, Lemon Grass, Guinea Grass, Vetiver, Citronella grass, Sugar Cane
Harvesting with machines	Herbs: Sugar Beet, Mustard, Ginger, Green Gram, Radish, Turmeric, Ashwagandha, Groundnut, Cumin Shrubs: Jethimadh, Potato

3 Agrivoltaic systems design considerations

There could be two broad approaches to developing agrivoltaic projects:

(1) A brownfield agrivoltaic project – planning for utilisation of existing solar power plant sites for agricultural purposes and selecting crops that will be suitable for the site and can co-exist with the solar power plant without impacting its performance and with no significant changes or investment required.
(2) A greenfield agrivoltaic project – A new site where a PV power plant and agricultural activities are planned together. Such sites may already be used for agricultural purposes and PV power plants are planned to use the land for dual purposes to enhance productivity (agriculture and energy).

For both approaches, as mentioned above, the following fundamental considerations are necessary for designing an agrivoltaic project.

(1) Structure and crop height: Matching crop height to a mounting structure of a PV power plant to avoid hindrance to crop growth and any shadow on the PV modules.
(2) Access to sunlight: Solar fields (placement of PV arrays) and agricultural fields shall be placed so crops get adequate access to sunlight according to their DLI (daily light integral) requirement. As different zones in the solar field site will have different levels of sunlight, crops shall be selected based on minimum DLI requirements and sunlight availability due to shading from PV modules.
(3) Safety of personnel: In solar power plants, PV modules are connected in series, resulting in a DC voltage of 300 V to 1500 V, depending upon the size of the plant and the type of inverters used. The string and array cables carrying such voltage are laid across the solar field and mounting structure. Similarly, the output of PV inverters is around 400 V AC, which will be further stepped up to 11 kV or 33 kV in a utility-scale plant. Exposure to such voltages is hazardous and fatal. In an agrivoltaic setup, in addition to the personnel working for the power plant, other personnel will also be involved in agricultural activities. Therefore, utmost care must be taken in designing electrical safety considerations for agrivoltaic projects.
(4) Safety of power plant and equipment: The life and performance of PV power plant and equipment can be affected due to electrical faults (such as over current/over voltage/arcing), mechanical damage (damage of cables/PV modules/structure) and poor maintenance practice. In an agrivoltaic setup, PV plants will be exposed to multiple agricultural activities during sowing, nursing and harvesting. Depending upon the method of sowing/nursing/harvesting and tools and equipment used for such activities, the risk of mechanical damage is to be assessed and appropriate measures considered in the design for the protection of PV modules, cables and other equipment.
(5) Design optimisation for cost: To achieve the desired return on investment, carrying out a life cycle cost-benefit analysis for agrivoltaic projects, particularly greenfield projects is essential. Based on the priority of expenditure vs. income for the project life cycle, the design approach should be optimised for maximum return on investment.

The following section discusses the design considerations of ground-mounted PV plants in an agrivoltaic setup.

3.1 Mounting structure design considerations

Ground-mounted PV systems are generally installed with fixed structures with a suitable tilt angle facing south (facing north in the southern hemisphere), fixed structures with a provision to change the tilt angle a few times in a year and single-axis tracking systems rotating east to west on a horizontal N-S axis. Two-axis tracking arrays are also employed in selective projects where the structure rotates both the N-S and E-W axis, aligning the PV array to the direct beam angle of the sun throughout the day in all seasons. General guidelines for PV array mounting structures are given in IS/IEC 62548: 2016 Photovoltaic array design requirements and IS/IEC TS: 62738: 2018 Ground-mounted photovoltaic power plants – Design guidelines and recommendations [26][27][28][29].

The following are the essential factors in designing a structure for ground-mounted PV arrays.

- Adequate space between two rows must be kept to avoid shadow.
- Access must be there to reach each module without stepping on it.
- Optimum tilt angle for maximum generation for a fixed tilt structure.
- A minimum tilt of 10º to reduce material accumulation (dust, etc.) on the PV array.
- Use of corrosion-resistant materials suitable for the lifetime of the system.
- Shall be rated for minimum wind loading as per the basic wind speed of the site.
- Design consideration to allow thermal expansion/ contraction of the PV modules as per site conditions.

For an agrivoltaic setup, the following factors should be considered based on the site location and type of crops to be grown in the solar field areas.

3.1.1 Height of the structure

The structure's height is one of the most critical factors for greenfield agrivoltaic projects. Structure height should be selected based on the typical maximum height of the crops and vice versa to avoid any obstruction to the growth of crops and there should not be any shadow on the solar panels from the grown crops. It is also essential to consider if there is any possibility of damaging solar modules during sowing, nursing and harvesting crops due to the lower height of the solar panels. Avoiding shadow from the crops on the solar arrays should be considered from 9 a.m. to 4 p.m. (This time should be adjusted based on solar time). Table 1 in the previous section provides a classification of typical crops cultivated in India based on typical maximum height.

For brownfield agrivoltaic projects, existing PV plants' ground clearance (height of the lowest part of PV modules) is typically kept at 50 cm to 100 cm. For such projects, increasing the height of the structure or rearranging the solar field for agricultural purposes may not be justified for economic reasons. Therefore, the selection of crops according to the maximum typical height and placement of agricultural fields based on the availability of sunlight should be considered. The availability of sunlight and subsequent daily light integral (DLI) for crops at different zones of solar fields is discussed in the next section.

For greenfield agrivoltaic projects, it is crucial to understand whether certain crops must be grown on the site due to local climate, soil or economic reasons. If the choice of crops is limited, the mounting structure for the PV power plant shall be as required for the growth of proposed crops. However, it is worth mentioning that the higher the structure height, the higher the structure cost due to increasing wind loading and weight of the structure materials. Therefore, structure height should be finalised based on overall techno-economic analysis and the power plant's safety in the event of higher wind loading conditions.

Figure 1 below shows different possible heights for equator-facing fixed tilt structures in an agrivoltaic setup. This figure shows two configurations of structure – one with two PV modules in portrait orientation and the other with one PV module in portrait orientation or two in landscape orientation. For both configurations, six different possible heights are considered. Maximum ground clearance is considered 3 m. The availability of sunlight and subsequent daily light integral (DLI) for crops at different zones of solar fields are simulated using the System Advisor Model (SAM) for both configurations at all different heights [25].

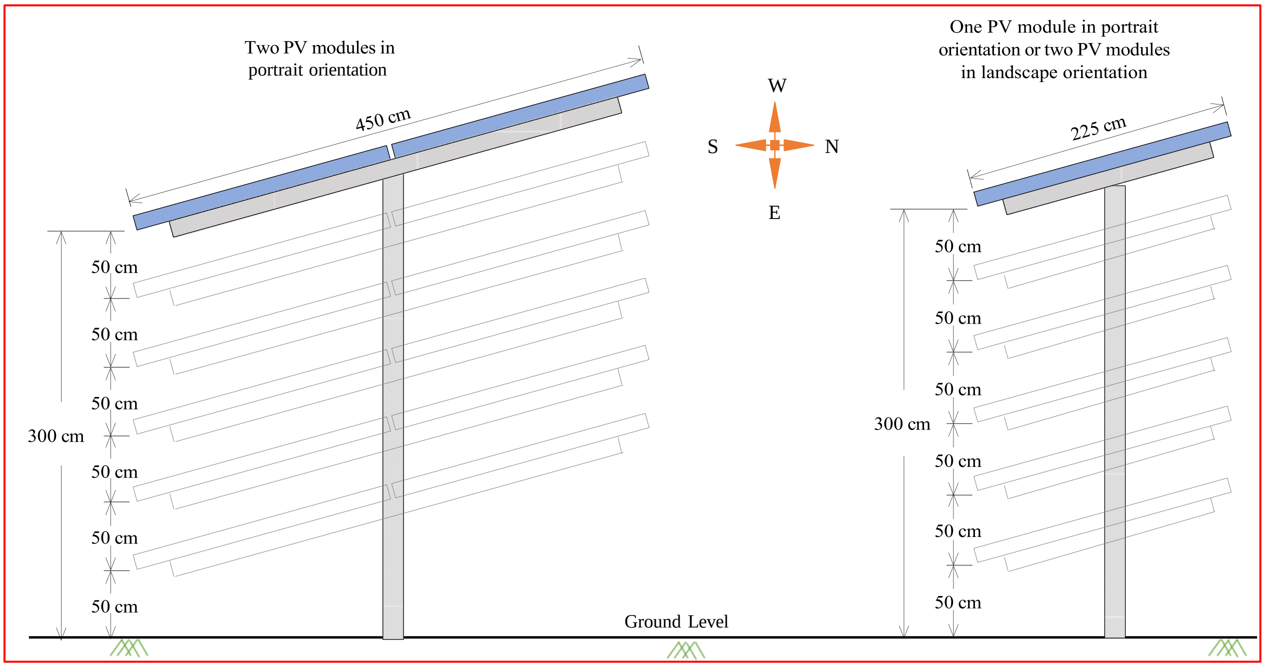

Figure 1: Different possible heights for equator-facing fixed tilt structure in agrivoltaic setup

Similarly, Figure 2 shows an east-west facing single-axis tracker and vertically installed fixed structure. In the single-axis tracking system, one module is installed in portrait orientation and 70 to 80 modules are fixed in one tracker. Two modules can be installed in landscape orientation for a vertically installed fixed structure. Ground clearance is kept between 50 cm to 100 cm for both cases. The availability of sunlight and subsequent daily light integral (DLI) for crops at different zones of solar fields are simulated using the System Advisor Model (SAM) for both configurations at 50 cm ground clearance. The results of the simulations are presented in the next section.

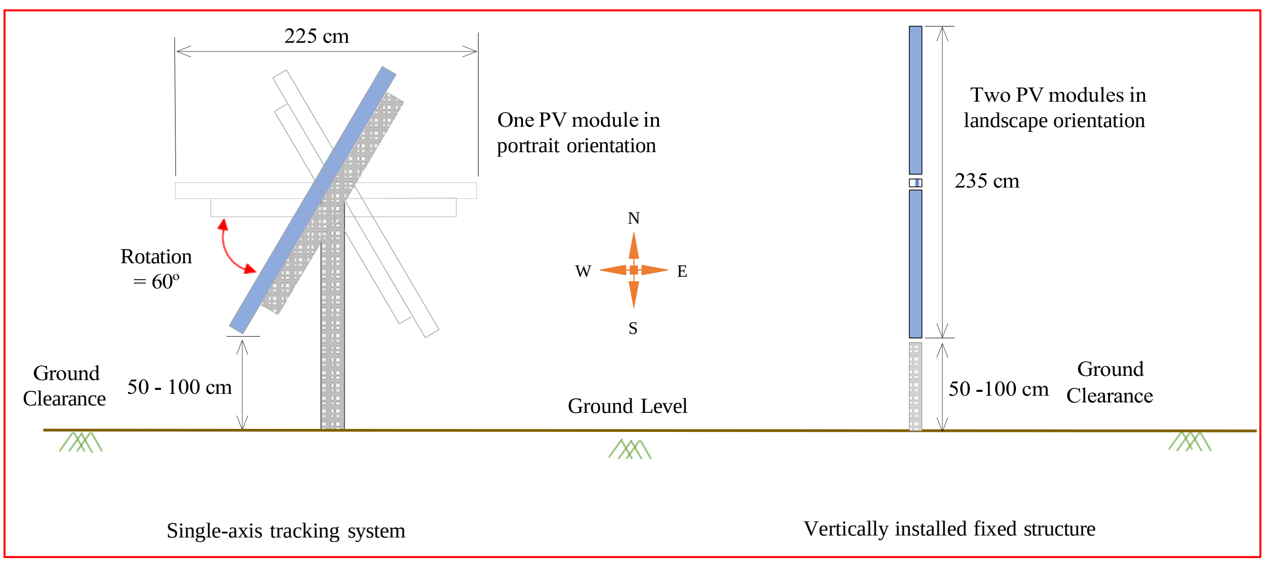

Figure 2: East-West facing single axis tracker and vertically installed fixed structure

3.1.2 Table size and placement of modules

It is recommended not to lay DC cables across roads or pathways in an agrivoltaic setup. Therefore, the table size should be such that it accommodates the modules connected in series (a string). The inverter input voltage and the minimum and maximum temperature of the site determine the number of modules in a string. The same needs to be determined in accordance with IS/IEC 62548: 2016 Photovoltaic array design requirement [26][27]. For a fixed tilt structure, when two modules are installed in portrait orientation, around 20 modules can be installed in one table, and when one module is installed in portrait orientation, around 10 modules can be installed in one table, as presented in Figure 3.

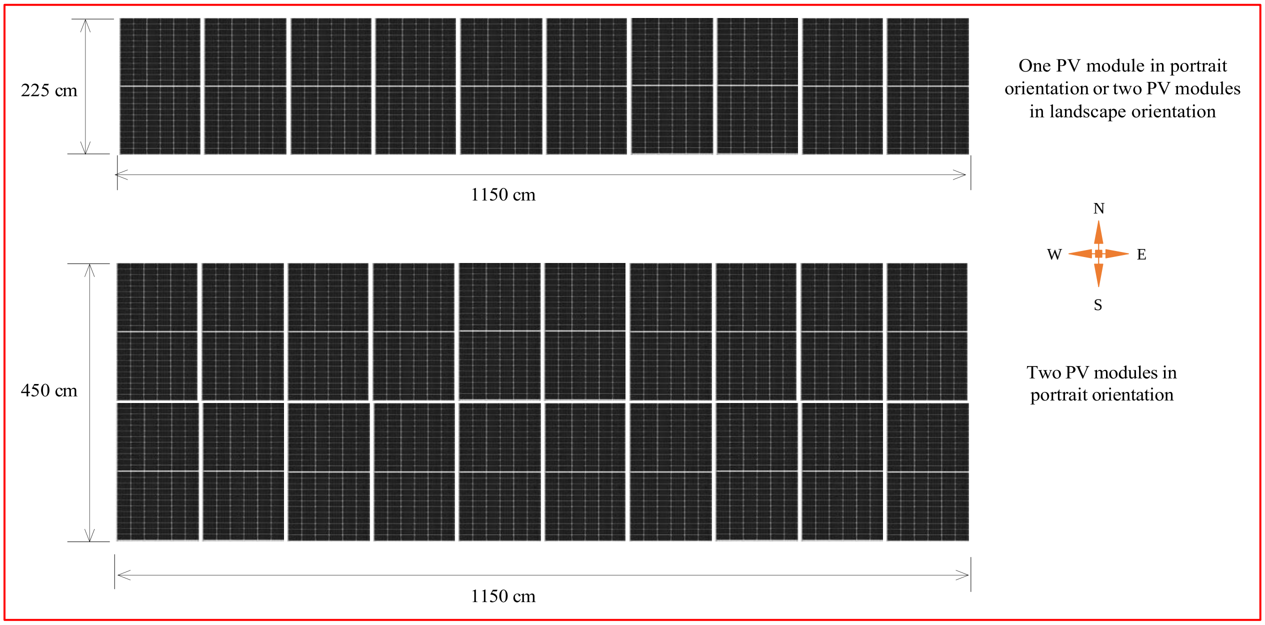

Figure 3: Placement of modules in two different tables in fixed tilt structures

In a single-axis tracking system, one PV module is fixed in portrait orientation and 70 to 80 PV modules are installed per tracker. PV modules will be facing east in the forenoon and west in the afternoon. The axis of the tracker will be in the North-South direction. Similarly, when two bifacial PV modules are installed vertically in landscape orientation. Modules will be facing east and west direction and not more than 2 strings (around modules per string based on the inverter input voltage) shall be used to make one table. These are illustrated in Figure 4 and Figure 5.

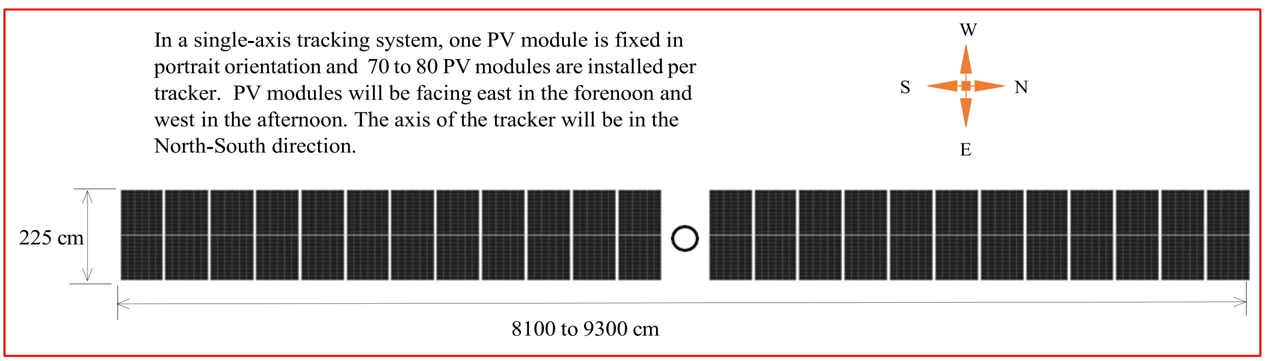

Figure 4: Placement of modules in a single-axis tracking structure

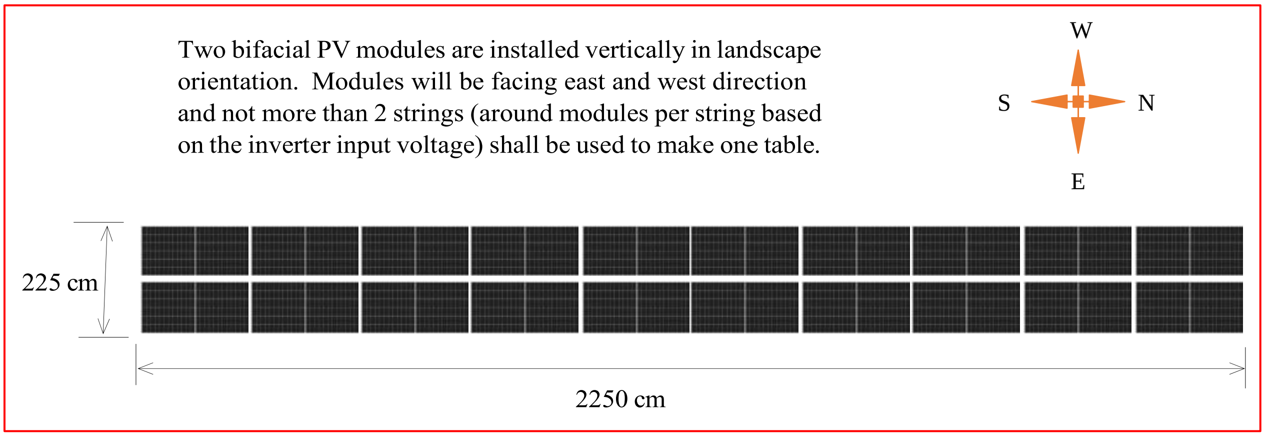

Figure 5: Placement of modules in a vertically installed fixed structure.

3.1.3 The tilt angle of the structure

The PV arrays are mounted on a structure in the following manners:

(1) Equator-facing fixed-tilt arrays
(2) Equator-facing adjustable tilt arrays
(3) East-West facing single-axis tracking arrays
(4) Two-axis tracking arrays

The main objective of choosing a type of structure is to generate maximum energy at a location based on the sun's position and sun movement during the year. However, a decision is made to achieve performance and cost objectives for a particular site.

Fixed tilt arrays are installed at a fixed tilt angle facing south (facing north in the southern hemisphere). The optimum tilt angle for annual energy generation is equal to the latitude angle up to 20^o per IS/IEC TS 62738: 2018 Ground mounted photovoltaic power plants design guidelines and recommendations [28][29]. However, a lower tilt angle in the range of 5^o to 20^o is used to reduce wind loading and the cost of the structure.

When PV modules are installed at a lower tilt (less than 10^o), there will be more accumulation of dust or dirt as wind or rain will not efficiently remove specks of dirt. In such cases, rainwater or cleaning water remains accumulated at the bottom of the modules when the module frame does not have drainage slots at the corners. In an agrivoltaic setup, more dust will likely be generated from agricultural activities, particularly during crops' sowing and harvesting time. Therefore, a minimum tilt of 10^o and preferably 15^o or more should be considered to maximise the self-cleaning of modules.

Equator-facing adjustable tilt arrays are fixed-tilt arrays with a provision to change the tilt angle once or more in a year based on the sun's position. A higher tilt angle is set for the winter months and a lower one for the summer months. This type of system is generally not used in large PV power plants due to increased wind load in the higher tilt position and maintenance cost.

Single-axis tracking arrays are installed on a structure which rotates on a horizontal north-south axis to follow the sun's path from morning to evening. PV modules will face east in the morning and west in the afternoon. The maximum tilt towards east and west with respect to the horizon is 60^o.

Two-axis tracking arrays are installed on a structure that rotates PV modules on the north-south and east-west axes, allowing PV modules to always follow the sun during the day. This type of structure is not widely used due to its high cost, higher self-consumption and vulnerability to wind loading.

For an agrivoltaic project in India, tilt angles are recommended for fixed-mounting structures based on the geographical location of the Agro-climatic zones, as presented in Figure 6 and Table 7 below.

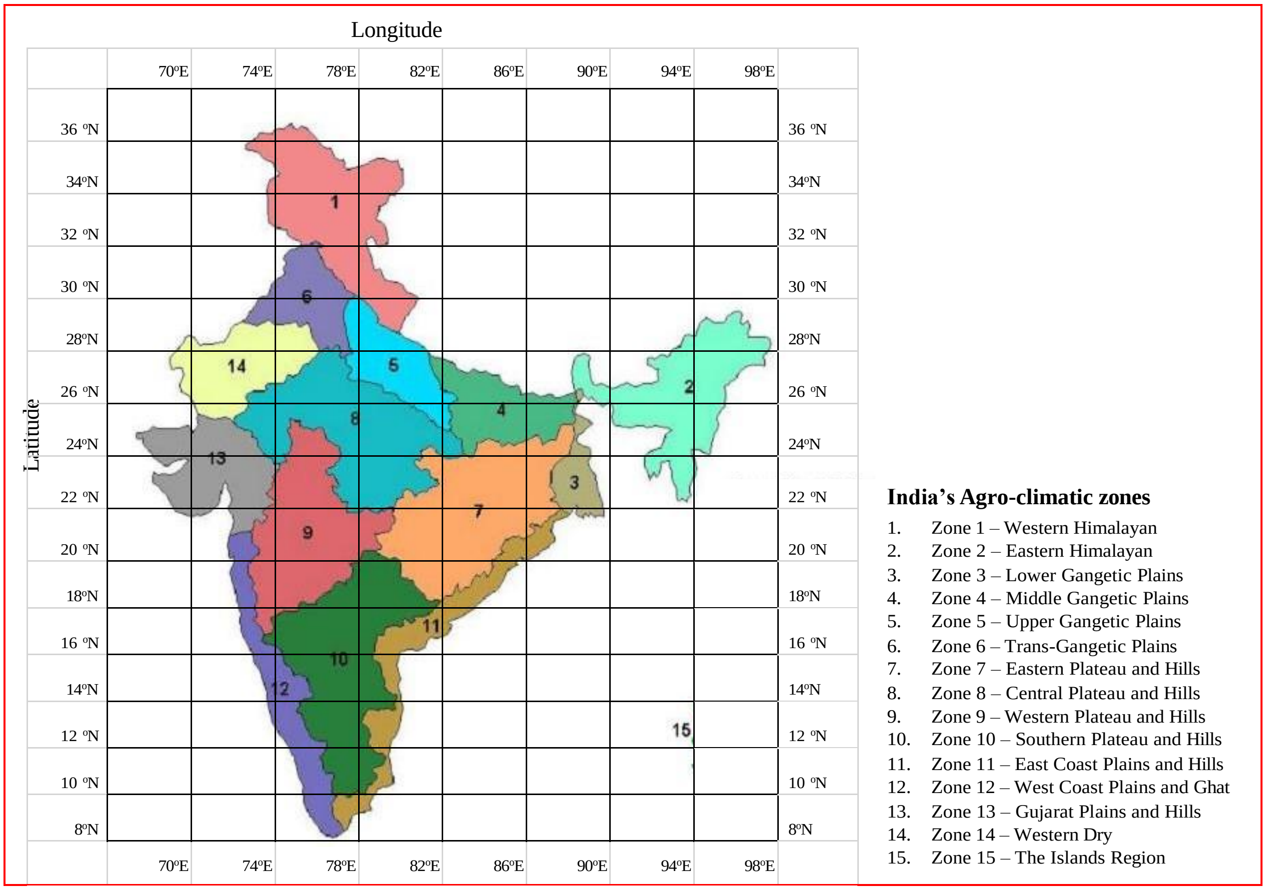

Figure 6: Latitude and Longitude of India's Agro-climatic zones (Indicative)

Table 7: Recommended tilt angle for fixed mounting structures

Geo-climatic regions	Agro-climatic & Geographical regions	Latitude	Recommended Tilt angle
The Himalayan Region	Zone 1: Western Himalayan Region: Jammu and Kashmir, Himachal Pradesh and Uttarakhand	Lat: 27^{o}E to 37^{o}E Lon: 73^{o}N to 81^{o}N	20^o to 30^o
	Zone 2: Eastern Himalayan Region: Sikkim, Darjeeling (West Bengal), Assam Hills, Arunachal Pradesh, Nagaland, Manipur, Mizoram, Tripura and Meghalaya	Lat: 22^{o}E to 29^{o}E Lon: 84^{o}N to 98^{o}N	20^o to 25^o
The Northern Plains	Zone 3: Lower Gangetic Plains: Eastern Bihar, West Bengal, and Assam valley.	Lat: 22^{o}E to 28^{o}E Lon: 87^{o}N to 95^{o}N	20^o to 25^o
	Zone 4: Middle Gangetic Plains: Eastern Uttar Pradesh and Bihar (except Chotanagpur plateau)	Lat: 24^{o}E to 28^{o}E Lon: 82^{o}N to 88^{o}N	20^o to 25^o
	Zone 5: Upper Gangetic Plains: Central and western parts of Uttar Pradesh.	Lat: 25^{o}E to 30^{o}E Lon: 73^{o}N to 81^{o}N	20^o to 25^o
	Zone 6: Trans-Gangetic Plains: Punjab, Haryana, Delhi, Chandigarh and Ganganagar district of Rajasthan	Lat: 28^{o}E to 32^{o}E Lon: 77^{o}N to 82^{o}N	20^o to 25^o

Geo-climatic regions	Agro-climatic & Geographical regions	Latitude	Recommended Tilt angle
The Western Arid Region (Thar Desert)	Zone 14: Western Dry Region: Western Rajasthan west of the Aravallis	Lat: 25ºE to 27ºE Lon: 69ºN to 76ºN	20º to 25º
The Central Highlands	Zone 7: Eastern Plateau and Hills: Chotanagpur plateau Rajmahal hills, Chhattisgarh plains and Dandakaranya.	Lat: 18ºE to 25ºE Lon: 80ºN to 88ºN	15º to 20º
	Zone 8: Central Plateau and Hills: Bundelkhand, Bhander plateau, Baghelkhand, Malwa plateau and Vindhyachal hills.	Lat: 22ºE to 28ºE Lon: 72ºN to 83ºN	20º to 25º
The Deccan Plateau	Zone 9: Western Plateau and Hills: Southern part of the Malwa plateau and Deccan plateau (Maharashtra)	Lat: 17ºE to 25ºE Lon: 73ºN to 80ºN	15º to 20º
	Zone 10: Southern Plateau and Hills: Southern Maharashtra, Karnataka, western Andhra Pradesh and northern Tamil Nadu.	Lat: 10ºE to 20ºE Lon: 74ºN to 82ºN	10º to 20º
The Coastal Plains and Islands	Zone 11: East Coast Plains and Hills: Coromandel and Northern Circar coasts, coasts of Andhra Pradesh and Orissa.	Lat: 9ºE to 22ºE Lon: 76ºN to 88ºN	10º to 20º
	Zone 12: West Coast Plains and Ghat Region: Malabar and Konkan coasts and the Sahyadris	Lat: 8ºE to 21ºE Lon: 72ºN to 77ºN	10º to 20º
	Zone 13: Gujarat Plains and Hills: Kathiawar and fertile valleys of the Mahi and Sabarmati rivers	Lat: 21ºE to 26ºE Lon: 68ºN to 74ºN	15º to 25º
	Zone 15: The Islands Region: Andaman-Nicobar and Lakshadweep	Lat: 10ºE to 16ºE Lon: 70ºN to 95ºN	10º to 15º

3.2 Agrivoltaic plant layout and site planning

For ground-mounted PV power plants, the main criteria and design objectives for layout planning and equipment positioning considered are:

- Field segments are placed such that there is no variation in orientation and tilt angle;
- Obstruction-free access to each PV module installed in the field segment;
- Provision for access to roads for the movement of equipment, goods and personnel;
- Access roads have adequate turning radius for the free movement of vehicles;
- Provision for cable trench and drainage system alongside the road;
- Tables are placed such that DC string cables do not cross any pathway;
- DCCB and inverter should be placed to ensure minimum crossover of DC cables;
- DCCB and inverter stations are placed such that they are easily accessible during the time of operation and maintenance and situations of fault;
- Inverters are installed such that the overall DC cable voltage drop is less than 3%;
- Adequate free areas are kept for the installation of containerised inverter-transformer stations.

In an agrivoltaic setup, the planning of solar and agricultural field segments is equally important.

3.2.1 Planning of solar field segment

Solar fields are planned for optimum utilisation of available area, minimum cable loss, and strategic operation and maintenance of the plant. For large utility-scale power plants, the land parcel is divided into several solar field segments to accommodate 1 MW to 2 MW in each field segment. Table 8 shows the land area required by solar field segments for different structure types. The indicative field segment also includes boundary areas and a road on one side.

Table 8: Land area required by solar field segment for different structure types

Sl. No.	Structure type and table size	Interrow gap (meter)	Field segment capacity	Field segment area (Hectare)
1	Fixed tilt array with 2 x 10 modules per table	4	1 MW_p	1.22
2	Fixed tilt array with 1 x 20 modules per table	4	1 MW_p	1.74
3	Single axis tracking with 80 modules per tracker	4	1 MW_p	1.75
4	Fixed tilt array vertically installed 2 x 10 modules per table	7.6	1 MW_p	1.91

While planning solar field segments, it is essential to consider appropriate interrow gaps to avoid shading. The interrow spacing required to avoid shadow will be variable based on the latitude of the place. Considering the longest shadow on 21st December (after 9:30 am and before 3:30 pm), the maximum gap between two rows for different locations has been determined for different locations as shown in Table 9.

Table 9: Minimum gap requirement between two rows for different locations

Sl. No.	Geo-climatic region and specific Location	Tilt Angle	Minimum gap between two rows (meter)			
			Fixed tilt array with 2 x 10 modules per table	Fixed tilt array with 1 x 20 modules per table	Single axis tracking with 80 modules per tracker	Vertically installed array 2 x 10 modules per table
1	Region 1: Srinagar Lat: 34.08° N	30	4.98	2.49	4.31	4.98
2	Region 2: Delhi Lat: 28.7° N	25	3.5	1.75	3.59	4.14
3	Region 3: Jaisalmer Lat: 26.9° N	25	3.22	1.62	3.30	3.81
4	Region 4: Raipur Lat: 21.25° N	20	2.22	1.11	2.81	3.25
5	Region 5: Ratnagiri Lat: 16.99° N	15	1.47	0.73	2.46	2.84
6	Region 6: Kozhikode Lat: 11.26° N	10	0.73	0.36	1.81	2.09

However, the gap between two rows is not only determined to avoid shadow but also to fulfil the requirement of movement of vehicles/equipment for operation and maintenance and safe access to personnel to carry required tools and materials. A minimum interrow spacing of 4 m is recommended for fixed-tilt mounting systems for maintenance requirements. The tracker manufacturers recommend the centre-to-centre spacing of 6.3 m between two rows for the single-axis tracking systems.

3.2.2 Planning of agricultural field

The following factors must be considered for planning agricultural fields in an agrivoltaic setup.

(1) The maximum typical height of the crops
(2) The minimum daily light integral (DLI) requirement
(3) Typical root penetration/ spread

(4) Plant life and sowing and harvesting time
(5) Method of sowing and harvesting and tools and equipment used
(6) Method of land preparation and tools and equipment used

These critical plant characteristics for agrivoltaic setup have been discussed in the previous section of this paper. Different crops are classified based on typical maximum height (Table 1), minimum DLI requirement (Table 2), typical root penetration (Table 3), plant life and sowing /harvesting time (Table 4) and method of sowing and harvesting (Table 5 & Table 6).

In an agrivoltaic setup, crops can be cultivated within the solar field segment and in open areas, unused areas and boundaries. Most agricultural field segments will be planned around the solar field segment. Therefore, it is essential to understand the availability of sunlight and corresponding DLI in different locations of solar field segments. For planning agricultural field segments in unused open areas and boundaries, shadow analysis must be carried out to avoid shadows from the crop on the solar modules.

System Advisor Model (SAM) developed by the National Renewable Energy Laboratory (NREL) was used to perform simulation modelling for different configurations of agrivoltaic setup across six geo-climatic regions of India to derive available sunlight and corresponding DLI in solar field segments. Region-wise specific locations and different design configurations for performance modelling are presented in Table 10 below.

Table 10: System performance modelling with different design configurations for different locations

Sl. No.	Geo-climatic region and specific Location	Tilt Angle	Number of designs simulated with structure height (ground clearance) variation			
			Fixed tilt array with 2 x 10 modules per table	Fixed tilt array with 1 x 20 modules per table	Single axis tracking with 80 modules per tracker	Vertically installed array 2 x 10 modules per table
1	Region 1: Srinagar Lat: 34.05° N	30	0.5 m to 3 m (six designs)	0.5 m to 3 m (six designs)	-	0.5 m (one design)
2	Region 2: Delhi Lat: 28.65° N	25	0.5 m to 3 m (six designs)	0.5 m to 3 m (six designs)	0.85 m (one design)	-
3	Region 3: Jaisalmer Lat: 26.95° N	25	0.5 m to 3 m (six designs)	0.5 m to 3 m (six designs)	-	-
4	Region 4: Raipur Lat: 21.25° N	20	0.5 m to 3 m (six designs)	0.5 m to 3 m (six designs)	-	-
5	Region 5: Ratnagiri Lat: 16.95° N	15	0.5 m to 3 m (six designs)	0.5 m to 3 m (six designs)	-	-
6	Region 6: Kozhikode Lat: 11.25° N	10	0.5 m to 3 m (six designs)	0.5 m to 3 m (six designs)	0.85 m (one design)	0.50 m (one design)

The System Advisory Model, by default, divides the space between two successive PV array rows into ten evenly distributed zones and provides irradiance values at the midpoint of each of these zones as illustrated in Figure 7 below.

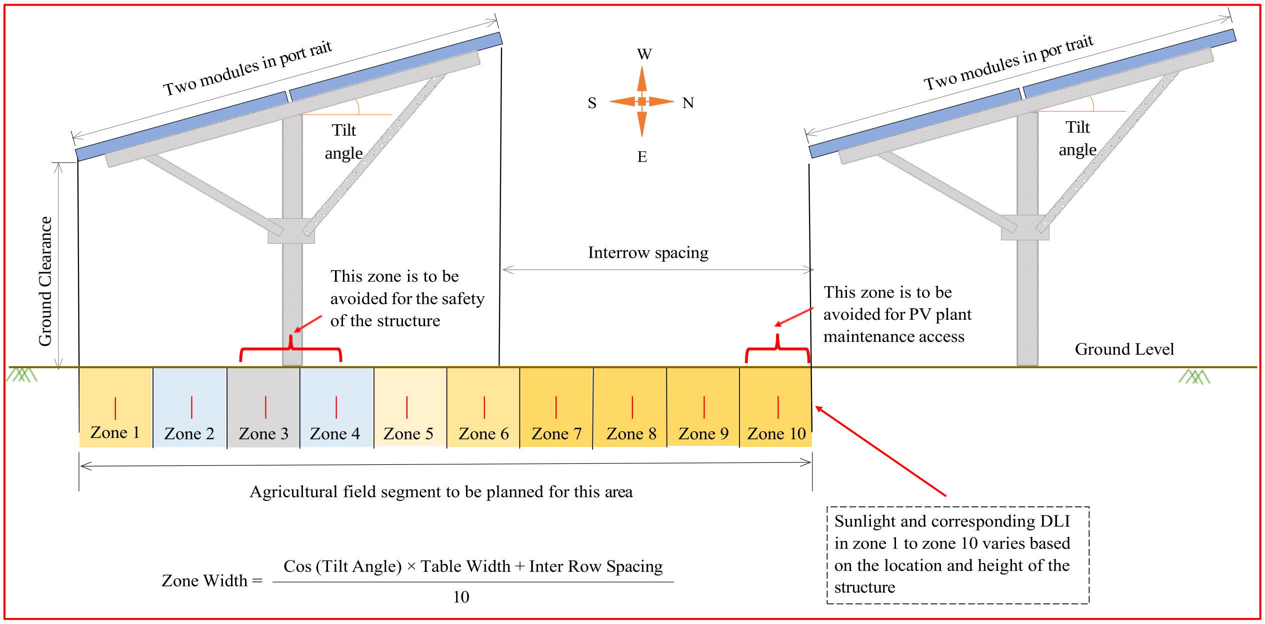

Figure 7: Illustration of fixed tilt array with 20 modules per table with 2 modules in portrait

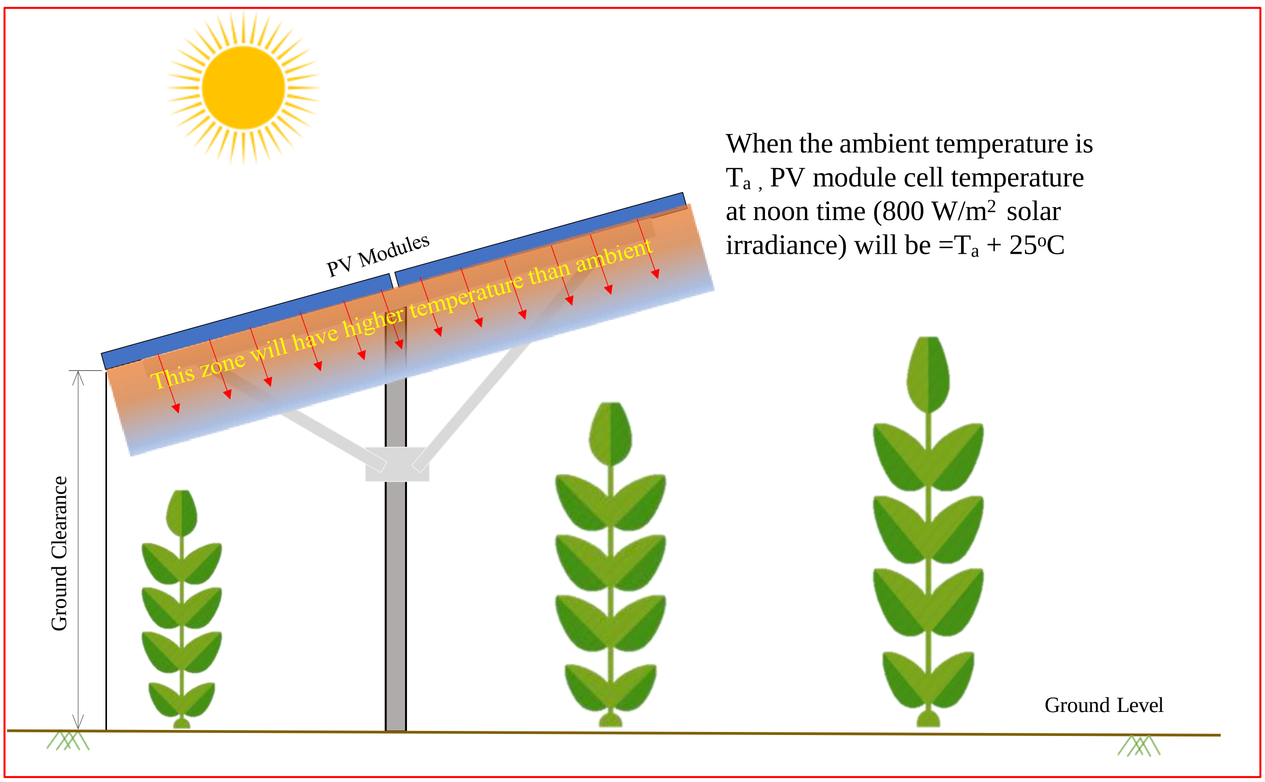

Figure 8: Illustration of temperature difference under PV arrays

The entire area in the solar field segment cannot be used for agricultural activities. The most critical areas to exclude from agricultural activities are – both sides of the structure foundation and the ground above cable trenches. Excluding at least 50 cm on both sides of the foundation/ piles is recommended. Similarly, at least 100 cm exclusion on each side of all major cable trenches is recommended. The roads and drainages will always be kept from any other activities. It is also important to keep a pathway always free on the lower side of the PV array for inspection and maintenance purposes. These provisions are illustrated in Figure 9 and Figure 10 below.

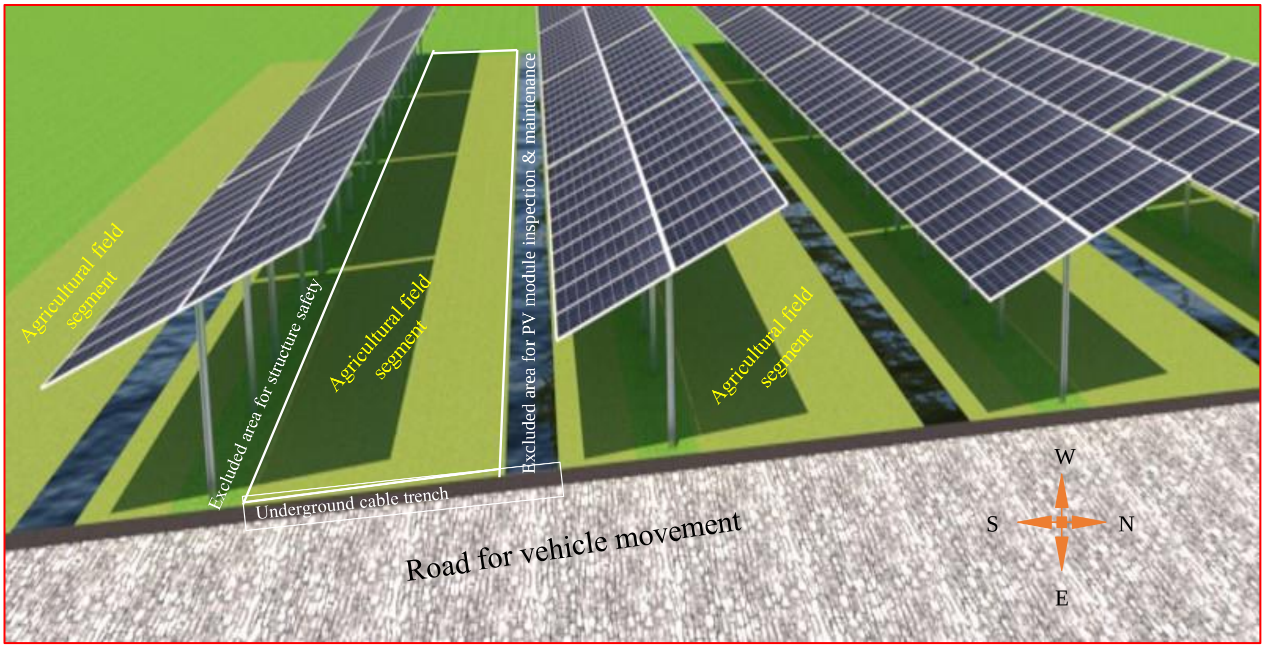

Figure 9: Agricultural field segments and excluded areas in a solar field with fixed tilt array with 2 x 10 modules per table

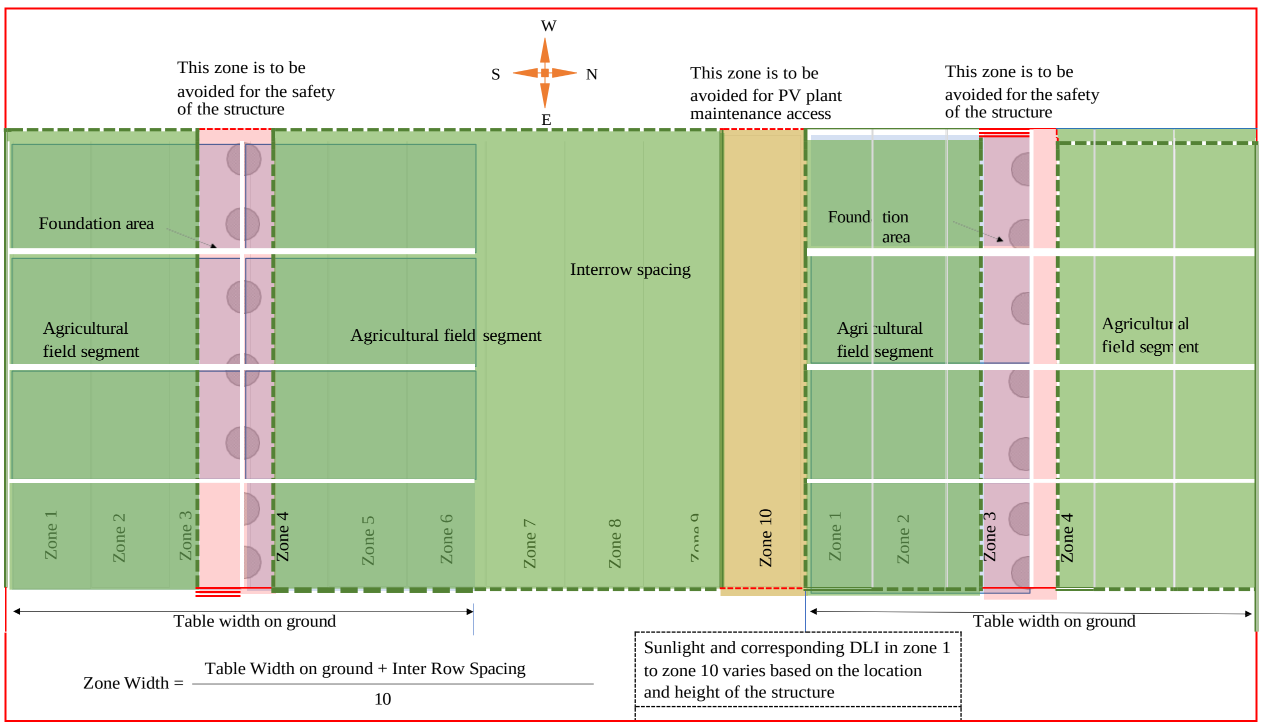

Figure 10: Plan view of agricultural field segments and excluded areas in a solar field with fixed tilt array with 2 x 10 modules per table

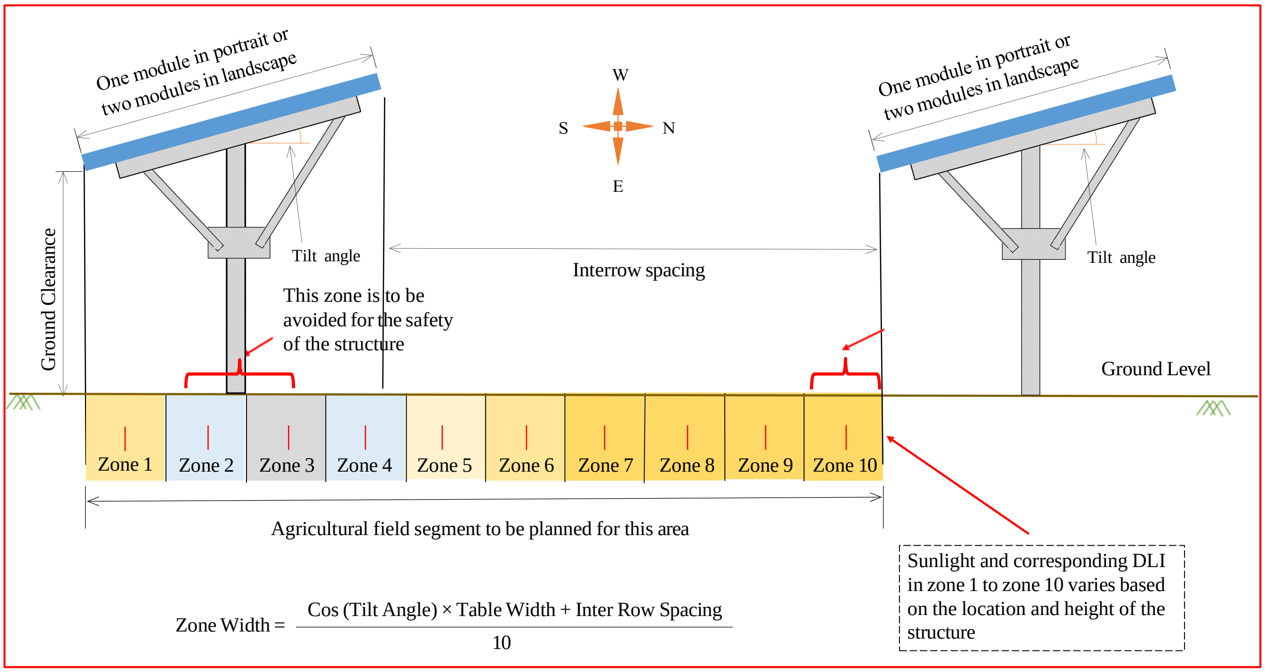

Figure 11: Illustration of fixed tilt array with 20 modules per table, 1 module installed in portrait

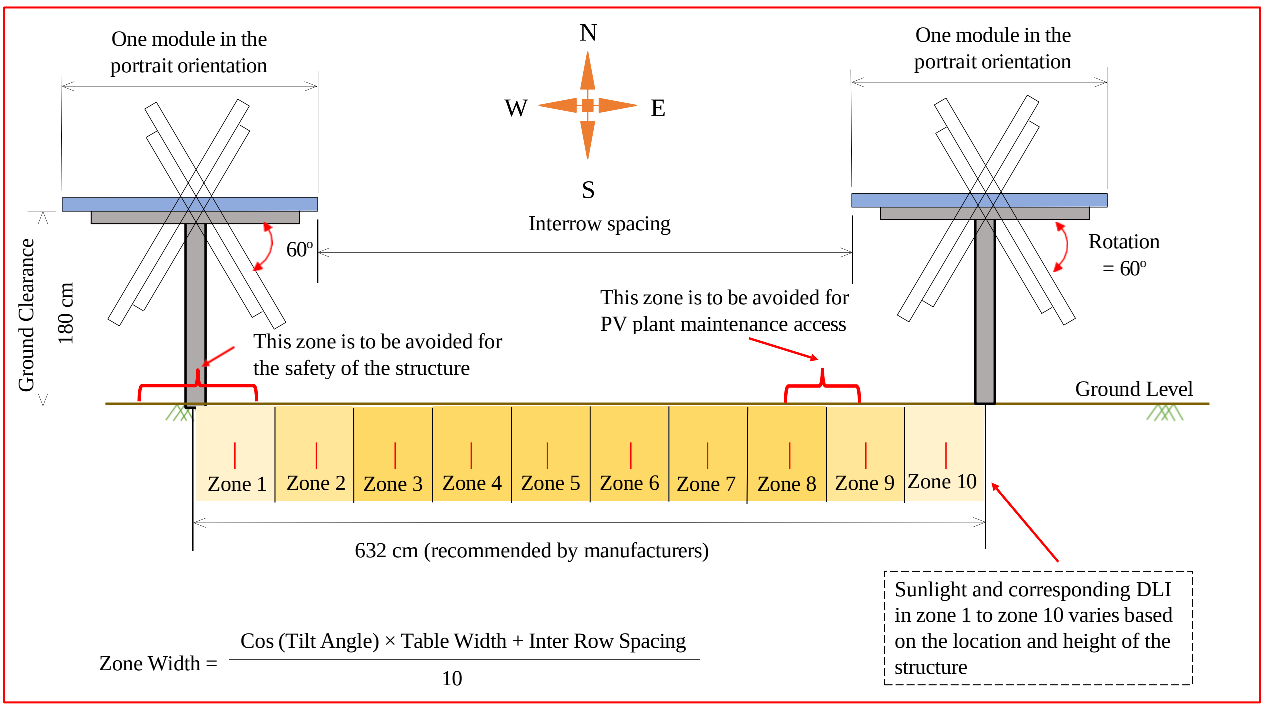

Figure 12: Illustration of single axis tracking system with 80 modules per tracker installed in portrait

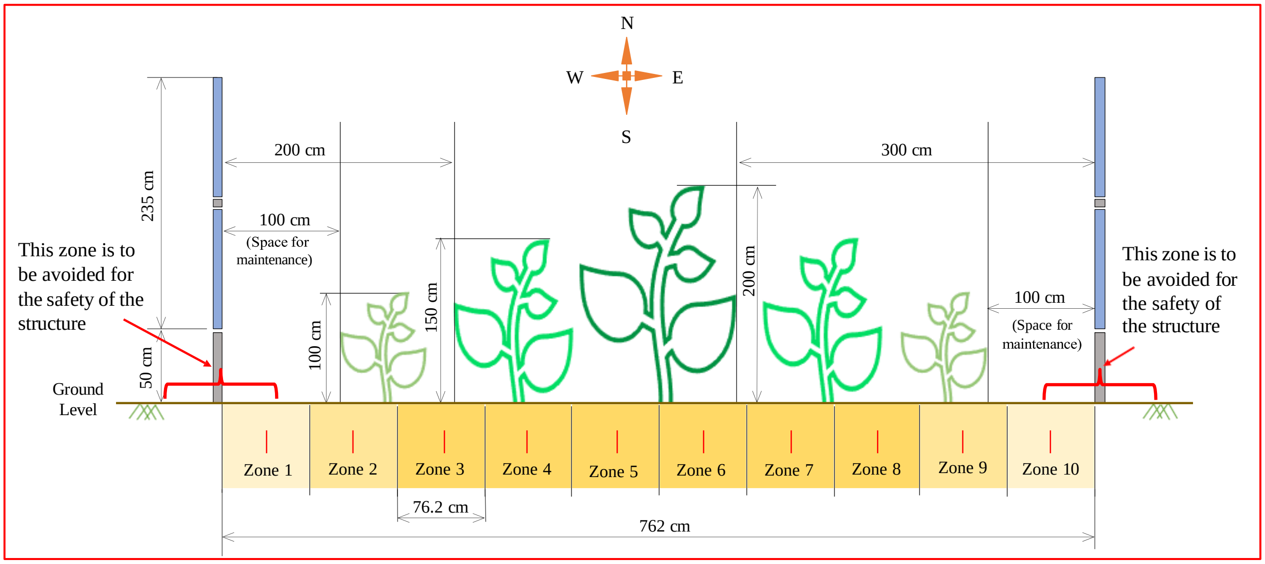

Figure 13: Illustration of a vertical array with 20 modules per table, 2 modules installed in landscape

3.3 Selection of crops based on structure height and available sunlight

The critical characteristics of different crops are presented in the previous section of this paper. In this section, Table 1 presents the typical maximum height, Table 2 presents the minimum DLI requirement, Table 3 presents typical root penetration, Table 4 shows plant life and sowing /harvesting time and Table 5 & Table 6 presents methods of sowing and harvesting of different crops cultivated in different geo-climatic regions. Based on these parameters, a selection index for crops for agrivoltaic projects based on sunlight requirement, growing season & height has been prepared and presented in Table 11.

Performance modelling has been carried out for six geo-climatic regions considering different design parameters such as table size, structure height, tilt angle, fixed tilt arrays, single axis tracker and vertically installed PV arrays, as presented in Table 10. The performance modelling provides the sunlight available within the solar field segments by dividing the space between two successive PV array rows (including the area underneath the PV array) into ten evenly distributed zones. The outcome of the performance modelling is solar radiation available in each zone of the solar field segment hourly for the entire year, total energy generation, specific energy yield and performance ratio of the PV power plant. The hourly solar radiation values have been converted to the daily average monthly and the same has been converted into equivalent DLI. This exercise has been carried out for all six geo-climatic regions for different design configurations. Matrices have been prepared for the selection of crops based on plant height, DLI and cultivation months for all six geo-climatic regions. The selection matrix for Srinagar (Lat: 34.05°N, Lon: 74.85°E, Tilt 30°) is presented in Figure 14 as an example.

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Period	Ground Clearance	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8	Zone 9	Zone 10	Open Field
Annual (Perennial)	0.5 m	A6 (10)	1	2	4	A6 (8)	A9 (20)	A12 (26)	A12 (29)	A12 (32)	A12 (33)	36
	1.0 m	B9 (16)	B3 (5)	3	4	B6 (8)	B9 (18)	B12 (24)	B12 (28)	B12 (30)	B12 (30)	36
	1.5 m	C12 (19)	C6 (9)	5	4	C6 (7)	C9 (16)	C12 (21)	C12 (25)	C12 (28)	C12 (28)	36
	2.0 m	D12 (19)	D6 (11)	7	6	D6 (7)	D9 (15)	D12 (20)	D12 (24)	D12 (26)	D12 (26)	36
	2.5 m	D12 (20)	D6 (12)	9	8	D6 (8)	D9 (14)	D12 (20)	D12 (23)	D12 (26)	D12 (26)	36
	3.0 m	E12 (21)	E9 (13)	10	9	E6 (9)	E9 (14)	E12 (19)	E12 (22)	E12 (24)	E12 (25)	36
	Ground Clearance	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8	Zone 9	Zone 10	Open Field
March - August	0.5 m	A5 (8)	2	3	5	A5 (13)	A11 (34)	A11 (41)	A11 (43)	A11 (43)	A11 (42)	45
	1.0 m	B8 (14)	3	3	5	B5 (12)	B11 (31)	B11 (39)	B11 (42)	B11 (43)	B11 (41)	45
	1.5 m	C11 (19)	C2 (5)	4	6	C5 (11)	C11 (28)	C11 (35)	C11 (39)	C11 (41)	C11 (38)	45
	2.0 m	D11 (22)	D5 (7)	5	6	D5 (10)	D11 (26)	D11 (34)	D11 (37)	D11 (40)	D11 (37)	45
	2.5 m	D11 (26)	D5 (9)	6	7	D5 (10)	D11 (24)	D11 (35)	D11 (38)	D11 (40)	D11 (39)	45
	3.0 m	E11 (28)	E5 (11)	7	7	E5 (10)	E11 (22)	E11 (33)	E11 (37)	E11 (39)	E11 (38)	45
	Ground Clearance	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8	Zone 9	Zone 10	Open Field
September - February	0.5 m	A7 (13)	1	2	3	A1 (4)	A1 (5)	A4 (11)	A7 (16)	A10 (21)	A10 (23)	27
	1.0 m	B10 (18)	B4 (7)	2	3	B1 (4)	B1 (5)	B4 (9)	B7 (14)	B7 (18)	B10 (20)	27
	1.5 m	C10 (20)	C4 (13)	5	3	C1 (4)	C1 (5)	C4 (7)	C7 (12)	C7 (15)	C10 (23)	27
	2.0 m	D7 (16)	D7 (15)	10	5	D1 (4)	D1 (4)	D1 (6)	D4 (10)	D7 (13)	D7 (14)	27
	2.5 m	D7 (16)	D7 (15)	12	9	D1 (5)	D1 (5)	D1 (5)	D4 (8)	D4 (11)	D4 (12)	27
	3.0 m	E7 (14)	E7 (14)	12	11	E4 (8)	E1 (5)	E1 (5)	E1 (7)	E4 (10)	E4 (12)	27
				Excluded zones for structure safety							Excluded zones for PV plant maintenance access	

Figure 14: Matrix for selection of crops based on plant height, DLI and cultivation months for Srinagar considering fixed tilt array with 2 x 10 modules per table

How to read this Matrix?

Refer to Table 11: Crop selection index based on sunlight requirement, growing season & height. In this table, a crop can be selected using a two-character index. The first character of the index is represented by an English capital letter A, B, C, D, E and F. The second character of the index is represented by a number 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11 and 12. The first index (capital letter) represents the typical maximum height of different crops, i.e. A (less than 50 cm), B (less than 100 cm), C (less than 150 cm), D (less than 200 cm), E (less than 300 cm) and F (more than 300 cm). These are placed in six columns on the right side of the table. The second index (number) represents the typical sunlight (DLI) requirement for the crop and cultivation months. For example, 1, 2, and 3 represent low-light crops that require daily light integral (DLI) of 3 to 6 mol/m²/day or equivalent solar radiation of 0.41 to 0.83 kWh/m^2/day. Number 1 represents crops cultivated during September- February, number 2 represents crops cultivated during March-August, and number 3 represents crops cultivated during all months (perennial).

Now follow Figure 14, where cells are filled with a two-character index and a number within a bracket or with only a number without a two-character index. The number within a bracket or without an index is the DLI value derived from the solar radiation available in a particular zone, at a specified height (ground clearance) of the structure during specified months or yearly. For example, the first cell on the top left is A6 (10), which refers to the Sugar beat in Table 11. This means sugar beet is a medium-light perennial crop with a typical maximum height of less than 50 cm, which can be cultivated in Zone 1 and Zone 5 under a PV array structure having minimum ground clearance of 50 cm.

Table 11: Selection index for crops based on sunlight requirement, growing season & height

Typical sunlight requirement	Cultivation months	INDEX	Typical maximum height of crops					
			Less than 50 cm	Less than 100 cm	Less than 150 cm	Less than 200 cm	Less than 300 cm	More than 300 cm
			A	B	C	D	E	F
Low light crops Daily light integral (DLI): 3 to 6 (mol/m²/day) Solar Radiation: 0.41 to 0.83 kWh/m^2/day	September - February	1	Centella asiatica (Brahmi Booti/ Mandukaparni) (herb)					
	March - August	2	Himalayan Mushroom (Gucchi) (herb)		Arrowroot (herb)			
	All months (perennial)	3					Coffee (shrub)	
Medium-light crops Daily light integral (DLI): 6 to 12 (mol/m²/day) Solar Radiation: 0.83 to 1.66 kWh/m^2/day	September - February	4	Carrot (herb) Cauliflower (herb)	Mustard (herb) Parsley (herb) Cow Pea (herb) Radish (herb)		Peas (shrub)	Sonamukhi (shrub)	
	March - August	5		Mung bean (herb) Green Gram (herb) Parsley (herb) Cow Pea (herb) Sarpagandha (shrub)		Cotton (herb) Vetiver (herb)	Okra/ Ladies finger/ Bhindi (herb)	

Typical sunlight requirement	Cultivation months	INDEX	Typical maximum height of crops					
			Less than 50 cm	Less than 100 cm	Less than 150 cm	Less than 200 cm	Less than 300 cm	More than 300 cm
			A	B	C	D	E	F
	All months (perennial)	6	Sugar beet (herb)	Ginger (herb) Tea (shrub) Aloe vera (herb) Guinea Grass Patchouli (shrub) Kariyatu (Andrographis paniculata) (herb) Poppy (herb)	Asparagus (herb) Soybean (herb) Turmeric (herb) Ashwagandha (herbs) Jethimadh (shrub)	Black Pepper (climber) Betel Leaves (climber) Sunamukhi (shrub) Cardamom (shrub) Citronella (grass) Cotton (herb) Fennel (herb) Vetiver (grass)	Asparagus (herb) Soybean (herb) Turmeric (herb) Ashwagandha (herbs) Jethimadh (shrub)	Jute (herb) Papaya (tree)
High light crops Daily light integral (DLI): 12 to 18 (mol/m²/day) Solar Radiation: 1.66 to 2.48 $kWh/m^2/day$	September - February	7	Black Gram (herb) Cabbage (herb) lettuce (herb) Spinach (herb)	Onion (herb) Rye (herb) Coriander (herb) Fenugreek (herb) Garlic (herb) Potato (shrub) Mint (herb)	Tobacco (shrub) Wheat (herb)	Snake Gourd (climber) Bitter gourd (climber)		
	March - August	8	lettuce (herb) Spinach (herb)	Onion (herb) Chili (herb) Eggplant (herb) Stevia Leaves (herb) Coriander (herb) Garlic (herb) Rye (herb)		Sesame (herb) Snake Gourd (climber) Bitter gourd (climber) Indian Bean (climber) Ash gourd (creeper/ climber)	Pearl millet (Bajra) (shrub) Guava Hybrid (shrub)	

Typical sunlight requirement	Cultivation months	INDEX	Typical maximum height of crops					
			Less than 50 cm	Less than 100 cm	Less than 150 cm	Less than 200 cm	Less than 300 cm	More than 300 cm
			A	B	C	D	E	F
	All months (perennial)	9	Sankhpuspi (herb) Groundnut (herb) Isabgol (herb) Cumin (herb)	Stevia Leaves (herb) Chicory (herb) Oats (herb) Chick Pea (herb) Berseem Clover (shrub) Mothbean (herb) Cluster Bean (herb) Fenugreek (herb) Marigold (herb) Mint Leaves (herb) Chili (herb) Chicory (herb) Brinjal (herb) Capsicum (herb)	Elephant foot yam (Herb) Linseed (Herb) Tomato (Herb)	Rasp Berry (shrub) Senna (shrub) Indigo (herb) Senna (shrub) Long bean (climber) French Bean (climber)	Sunn Hemp (shrub)	Sugar Cane (grass) Pigeon pea (tree) Castor (shrub) Annatto dye (shrub) Kiwi (tree) Mango (tree)
Very high light crops Daily light integral (DLI): More than 18 (mol/m²/day) Solar Radiation: More than 2.48 kWh/m^2/day	September - February	10	Pumpkin (creeper) Watermelon (creeper)		Poppy (herb)	Maize (herb) Bottle Gourd (climber)		
	March - August	11	Pumpkin (creeper) Watermelon (creeper) Zucchini (creeper)		Paddy Rice (herb)	Maize (herb) Blonde cucumber (climber) Bottle Gourd (climber)		
	All months (perennial)	12		Geranium (herb)				

4 Performance evaluation and cost impact

Specific yield and performance ratios (PR) have been derived for different design variations for all six sites using the System Advisor Model (SAM) using solar radiation data from the NREL National Solar Radiation Database. Values of specific yield and PR for all design variations are presented in Table 12. It is noted that the specific yield and performance ratio for fixed tilt arrays with two different table sizes and six different structure heights is the same for a single location. The performance ratio in a specific location is the same for all designs and varies for other locations due to variations of loss in the system due to temperature. Using a single-axis tracking system enhances energy generation by 10% in New Delhi with a capacity utilisation factor (CUF) of 19.95% and 19% in Kozhikode with a CUF of 22.89% compared to fixed tilt arrays. This indicates that using a single-axis tracking system is more beneficial for the locations near the equator. On the other hand, the energy generation of vertically installed bi-facial solar arrays was reduced by 21% in Srinagar (CUF 15.15%) and 40% in Kozhikode (CUF 11.44%). This indicates that vertically installed bi-facial modules perform better in locations away from the equator than near the equator.

The design variations used for the performance evaluation are:

Design 1 – Fixed tilt with a table for 20 modules with two modules installed in portrait (**Figure 7**)
Design 2 – Fixed tilt with a table for 20 modules with 1 module installed in portrait (**Figure 11**)
Design 3 – Single-axis tracker with a tracker table with 80 modules installed in portrait (**Figure 12**)
Design 4 – Vertical bifacial with a table for 20 modules with two modules installed in landscape (**Figure 13**)

Table 12: Specific yield and performance ratio of different designs at different locations in India

Geo-climatic region and design variation	Table size	Row spacing	Tilt Angle	Specific Yield ($kWh/kW_p/y$)	Annual PSH ($kWh/m^2/y$)	PR	CUF
Region 1: Srinagar Design - 1 (Fixed array)	2 × 10	5 m	30°	1680	2024	83%	19.18%
Region 1: Srinagar Design - 2 (Fixed array)	1 × 20	4 m	30°	1680	2024	83%	19.18%
Region 1: Srinagar Design - 4 (Vertical)	2 × 10	7.6 m	90°	1327	1598	83%	15.15%
Region 2: Delhi Design - 1 (Fixed array)	2 × 10	4 m	25°	1589	2037	78%	18.14%
Region 2: Delhi Design - 2 (Fixed array)	1 × 20	4 m	25°	1589	2037	78%	18.14%
Region 2: Delhi Design - 3 (Tracking)	1 × 80	4 m	0°	1748	2241	78%	19.95%
Region 3: Jaisalmer Design - 1 (Fixed array)	2 × 10	4 m	25°	1781	2283	78%	20.33%
Region 3: Jaisalmer Design – 2 (Fixed array)	1 × 20	4 m	25°	1781	2283	78%	20.33%
Region 4: Raipur Design – 1 (Fixed array)	2 × 10	4 m	20°	1682	1998	84%	19.20%
Region 4: Raipur Design – 2 (Fixed array)	1 × 20	4 m	20°	1682	1998	84%	19.20%

Geo-climatic region and design variation	Table size	Row spacing	Tilt Angle	Specific Yield ($kWh/kW_p/y$)	Annual PSH ($kWh/m^2/y$)	PR	CUF
Region 5: Ratnagiri Design - 1 (Fixed array)	2 × 10	4 m	15°	1681	2033	83%	19.19%
Region 5: Ratnagiri Design - 2 (Fixed array)	1 × 20	4 m	15°	1681	2033	83%	19.19%
Region 6: Kozhikode Design - 1 (Fixed array)	2 × 10	4 m	10°	1682	2063	82%	19.20%
Region 6: Kozhikode Design - 2 (Fixed array)	1 × 20	4 m	10°	1682	2063	82%	19.20%
Region 6: Kozhikode Design - 3 (Tracking)	1 × 80	4 m	0°	2005	2445	82%	22.89%
Region 6: Kozhikode Design - 4 (Vertical)	2 × 10	7.6 m	90°	1002	1222	82%	11.44%

4.1 The impact on cost parameters in agrivoltaic projects

The project design approach, selection of equipment site parameters and geographic locations highly influence the cost of developing solar projects. Therefore, the cost of developing solar projects may vary from site to site. Similarly, the cost of developing greenfield agrivoltaic projects is also determined by design approach, selection of equipment site parameters and geographic locations. The level of impact on cost parameters compared to conventional PV projects is presented in Table 13.

Table 13: The level of impact on cost parameters in comparison to conventional PV projects

Sl. No.	Cost parameters	Estimated cost in comparison to conventional PV projects			
		Brownfield agrivoltaic projects	Level of impact on cost	Greenfield agrivoltaic projects	Level of impact on cost
1	Land	None	None	None/High	None/Low
2	PV Modules	None	None	None	None
3	Inverters and inverter housing	None	None	None	None
4	DC side electrical	None	None	None/High	None/Moderate
5	AC system, substation and grid integration	None	None	None	None
6	PV array mounting structure & foundation	None	None	High	Moderate
7	Site development and civil infrastructure	None	None	None	None
8	System protection (over current & overvoltage)	None	None	None	None/Low
9	System safety from mechanical damage	Upgradation	Low	High	Low

Sl. No.	Cost parameters	Estimated cost in comparison to conventional PV projects			
		Brownfield agrivoltaic projects	Level of impact on cost	Greenfield agrivoltaic projects	Level of impact on cost
10	Protection for personnel safety including signages & markings	Upgradation	Low	High	Low
11	Installation cost	None	None	None	None
12	Operation and maintenance	None	None	High	Moderate

5 Conclusion

Agrivoltaics is not a 'one-size-fits-all' solution. With its potential to synergise renewable energy production and agriculture, it calls for careful customisation, considering regional specifics such as geographical locations, climatic and soil conditions, and agricultural practices. This study explores the prospective implementation of agrivoltaics across India's diverse geo-climatic zones, offering valuable insights and technical guidelines. It emphasises the viability of dual land use and integrating energy generation with agricultural production. A detailed analysis of crop suitability, PV array configurations, and region-specific solar irradiance data sheds light on the critical design parameters for optimising agrivoltaic systems.

The design and operation of agrivoltaic systems should factor in crop characteristics such as height, sunlight requirements, root penetration, and growth cycle. These characteristics have been systematically documented in this study. Advanced simulation tools like the ‘System Advisory Model’ demonstrate the interaction between diverse PV designs and the resultant solar irradiance across various regions. These insights facilitate optimal crop selection, paving the path towards achieving the maximum land equivalent ratio.

Performance ratios and specific yields, influenced by PV array configurations and geographical location, have revealed remarkable trends. For instance, in New Delhi and Kozhikode, single-axis tracking systems enhanced energy generation by 10% and 19%, respectively, compared to fixed tilt arrays, indicating a preference for locations closer to the equator. Conversely, energy generation diminished by 21% in Srinagar and 40% in Kozhikode with vertically installed bi-facial solar arrays, suggesting better performance in locations further from the equator.

The cost of developing agrivoltaic projects, akin to conventional solar projects, is contingent on several factors, including project design approach, equipment selection, site parameters, and geographic location. As a result, costs tend to vary from one site to another. While compared to conventional PV plant set-up, there will be a low to moderate increase in cost for agrivoltaic setup based on the design approach. The principal factors that influence agrivoltaic project cost are optimum uses of land for both purposes, PV array mounting structure design for specific crops, DC cables, additional protection required for the safety of personnel and system/equipment and enhanced operation and maintenance activities of PV plant.

In this paper, the methodology employed a two-step process to assess the feasibility of agrivoltaics. Initially, solar irradiation data was simulated under and behind the PV arrays. Subsequently, a thorough evaluation of suitable crops was conducted, considering the global trend of most agrivoltaic plants being extensions of pre-existing PV installations. As an alternative approach, a predetermined list of crops would be prepared, and the PV system could then be designed to optimise available space without compromising agricultural yield. This approach is preferable when cultivated crops hold substantial commercial value and farming is the primary income source. In such cases, the focus is balancing conserving agricultural productivity and enhancing land-use efficiency through PV generation.

Integrating agrivoltaics into India's renewable energy strategy holds significant promise for yielding substantial benefits. This study lays a strong foundation for such a transition, presenting a roadmap for the smooth integration of agricultural productivity and renewable energy generation. The study's outcomes are expected to provide valuable insights and guidelines for developing agrivoltaic projects in India, enriching understanding of the technical design aspects. However, the key to success lies in adopting a region-specific approach and cultivating a continuous learning and adaptation culture. Further research is required on implementing different design approaches and their impact on PV system performance and agriculture production.

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