Agrivoltaics in India: The Challenges and Opportunities

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Abstract – *Future land resource rivalry between agricultural and renewable energy may increase in several nations, including India. The concurrent utilization of land for photovoltaic (PV) power generation and agriculture is known as agrivoltaics, and it presents a viable solution. Research indicates that agrivoltaics can boost agricultural productivity and panel efficiency, which is why farmers and solar developers find it appealing. It offers a cursory analysis of Indian laws that are pertinent to the idea of agrivoltaics. It provides a starting point for talking about the potential of agrivoltaics in India and how it fits into the current energy transformation of the nation. With over a dozen pilot projects now implemented nationwide, India is leading the way in the adoption of agrivoltaics, which has expanded rapidly in the last few years around the globe.*

Keywords – Agrivoltaics; Agrivoltaics Project; Agrivoltaics Schemes; Photovoltaic.

1. INTRODUCTION

The utilization of land for both solar energy and agricultural systems, or agrivoltaics (APV), has significantly increased in the last several years [1]. A relatively new idea, agrivoltaics is already yielding positive outcomes in energy generation, food production and recently reducing conflicts between the two. The stability of agricultural yields is becoming a crucial component in guaranteeing farmers' financial gain because of climate change and also frequently increase in extreme weather events [2]. Due to human activity, global warming with +1.5 °C is quite likely to occur in future. Additionally, extreme weather events including heatwaves, dry period, and intensive rains will become more common [3]. The existing site that is ready for the installation of solar plants already has both the surface-mounted solar system (S-MSs) and the APV system (APVs). The payback period of S-MSs and the APV do not differ significantly, according to the resultant economic metrics, indicating that the APV is superior to the S-MSs. In the APVs, the cost-benefit ratio for agriculture is 1.5, indicating a positive value for the economic parameter. The idea of a solar agricultural farm enables the land to be used for different purposes, offering a number of advantages including higher net yields, lower expenses associated with electricity evacuation, and consistent revenue for farmers [4]. The APV parks are transformed into ecological infrastructure that is purposefully planned to serve as a didactic and scientific promotion tool as well as an instrument for enhancing regional culture. Thus, the opportunity to advance a more sustainable and effective environment and model of economic growth lies in the generation of clean energy, which plays a significant part in the ecological transition. The technique is centered on a holistic transformed strategy that extends with their specific design of APV fields in order to minimise biodiversity loss and ameliorate the adverse effects because of the human activities on environment. Also the three pertinent aspects (green infrastructure, services of ecosystem, and nature-based solutions (NBS)), the proposal's transformation actions are defined in accordance with Sustainable Development Goals (SDGs), understanding of the dynamics of the environment and terrain. [5].

In India, APV plants have capacities ranging from 3kWp to 3MWp. APV installations larger than 3MWp at the utility scale have not yet been implemented. There are no examples of corresponding technological, economic, or agricultural viability as a result. As of 2020, In terms of installed solar capacity, India now ranks fifth in the world, behind the US, China, Japan, and Germany. Its official solar generating fleet has grown to a capacity of about 36GW and now in 2024 it reaches 76GW [6]. A thermal power plant (TPP) near the project site is owned and operated by the investor of the proposed APV project. According to locals, the agricultural community and the TPP management have a symbiotic relationship that has helped the TPP strengthen the little village's economy in a variety of ways. Since the start of the project, i.e., prior to the initial commissioning and for subsequent increases in capacity, the TPP operator has purchased land from farmers on several occasions. In addition to appropriate compensation, the TPP management gave the impacted farmers work [7]. The modifications made to the dry-hot valley's soil properties after the installation of an APVs. This is the first study that is aware of examining how APVs impact the condition of the soil in arid, hot valleys that are eco-fragile [8]. Drip irrigation, rainwater collection, and other water-saving methods may give priority to APVs over those that just draw water from the ground. Additionally, the water that was used to clean the solar modules might be put to better use in

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farming. This would, however, limit the modules' ability to be cleaned with chemical agents [9]. These installations of agrivoltaics give an idea of what potentially economically viable solutions may already look like. Being the pioneer in introducing agriculture between panel arrays, it produced 0.87 tons of ginger per acre at a net profit of 75,361 INR per acre. Similarly, the productivity of bottle gourd under PV was around 1.16 tons per acre with net profit 5,051 INR per acre. The business also examined the financial gains from growing different crops beneath the solar panels [10]. In India's pilot programs suggests that semi-arid and arid areas might offer ideal circumstances for maximizing the benefits of energy generating and agriculture working together [11]. Crop development can be directly impacted by the microclimatic conditions that lie underneath these systems, which include elements like air temperature, solar radiation, humidity, wind speed, soil temperature, and moisture. Specifically, solar radiation is thought to be the factor most impacted [12]. The open-field farming method used in India has not been compared to the morphological criteria, such as crop performance and yield, in APVs. Turmeric belongs to the Curcuma longa botanical family, which has several uses, including those as a spice, coloring agent, skin care product, and traditional medicine [13]. A number of lettuce cultivars were cultivated under APV in one of the very few studies that was based on an actual field trial. APV had almost little effect on harvestable yields, depending on the cultivar and the distance between the above-mounted PV modules [14]. Conflicts have been found to be complexly influenced by climate change, especially in areas where populations strongly depend on resources that are vulnerable to the changing environment [15]. The closeness of an agrivoltaic plant to the current power delivery infrastructure is a crucial factor in its suitability for grid integration. It might take a long time and money to build transmission lines to link a facility [16].

2. CONCEPT OF AGRIVOLTAICS

APV combines solar panels with crops to optimize land usage. It is, in essence, a method of integrating solar panels with plants on agricultural land. You may share light, improve freshness, and decrease moisture loss by growing field crops and solar electricity in the same space. After the first photovoltaic water pumps were introduced in 1975, the process of combining solar technology with agriculture got underway [17]. Since then, photovoltaic applications in agriculture have consistently demonstrated a propensity toward diversification, progressing from the first watering of agricultural land to the current uses in agricultural automation, robotics, lighting, ventilation, and machines. Numerous criteria may be used to classify agrivoltaic systems. a standard classification that is compatible with local (weather-farming) characteristics and can precisely characterize each unique APVs globally [18]-[20].

3. METHODOLOGY

Using Web of Science and Scopus, a methodical review of the literature was part of the study process. High-citation, peer-reviewed works that were still available as of the present day were taken into consideration for the study. Journal publications (articles or reviews) and conference papers were considered. Key phrases for the search included APV* OR PV* OR "Solar PV* system*" OR "agri-PV* system*" OR agri-voltaic* OR Solar-APV* OR Agri-solar system* OR "solar-agrovoltaic* system*" OR "agro-voltaic* system*" OR agro-photovoltaic* OR agri-solar system OR ″ dual-use solar system" OR "solar farming" OR "solar sharing*" OR "PV agriculture*" OR "dual land use*" OR "photovoltaic greenhouse*" OR "agriculture* photovoltaic*" OR "greenhouse* PV*" OR "flexible photovoltaic panel*". "India's current agrivoltaic situation." Materials pertaining to laws, applications, policies, status, technological features, and prospects for agrivoltaic in India were examined. The authors expanded their search beyond academic study papers to include industry reports and studies, media pieces, information from government websites, and information on the continuous exploration and development of agri-photovoltaic systems [19].

4. SCOPE IN AGRIVOLTAICS

Even though conventional land-based solar photovoltaic (PV) plants have shown to be successful in producing power, research into novel and inventive solar applications (NISA) that provide unique benefits is becoming more and more important. The idea of dual-use or land-neutral applications in particular has become very popular. By utilizing non-traditional areas or combining solar panels with existing infrastructure, this technique aims to maximize the utilization of available land. We can eliminate conflicts over land usage, get beyond the restriction of land availability, and improve the overall sustainability and efficiency of the solar energy industry by utilizing these alternate uses. India's overall APV potential ranges from 3,156 GW to 13,803 GW, depending on the lowest and maximum scenarios used for different crops using different APV technologies in each district. Based on their land holdings, medium farmers (owning more than two hectares) and small farmers (having less than two hectares) are the two basic groups of farmer types for which the business model has been built. In addition to guaranteeing the continuation of farming operations, APV technology can offer the power distribution companies (DISCOMs) significant financial benefits in their supply operations. The APV capacity prediction spans 2024 to 2040. Under the moderate and optimistic scenarios, the cumulative capacity expansion is anticipated to be 20 GW and 60 GW of APV, respectively. A total of INR 81,424 crores would be needed to realize the 20 GW capacity (moderate case), and INR 2,13,858 crores will be needed to install 60 GW of APV in the nation. Improved exploitation of renewable energy resources and superior craftsmanship on the deployed technologies are guaranteed when the APV sector in India develops a competent workforce, which is essential to improving APV penetration. According to estimates, 1.1 lakh full-time equivalent (FTE) jobs would be needed in the moderate scenario to fulfill a demand of 20 GW of APV by 2040, and 3.38 lakh FTE jobs in the optimistic case to support different functions [9].

Table 1. Ongoing Agrivoltaics Project between 2021-2024 in India [10].

Project Name	Project Type Solar-energy	Generation Capacity
Krishi Vigyan Kendra(NHRDF) Ujwa, Delhi	Research project	110 kWp
Agrivoltaics plant near Parbhani, Maharashtra	Research project	1.4 MW
Sandhwani Solar Power Plant	Commercial project	250 kW
GroSolar Agri-PV Interspace System, Dhule, Maharashtra	Research project	1 MW
SunMasterAgri-PV System, Delhi, India	Research project	2 MW
Fish Pond Agri-PV System, Bhaloji, Rajasthan	Commercial project	30 kW

5. AGRIVOLTAICS PROMOTING SCHEMES IN INDIA

The Pradhan Mantri Kisan Urja Suraksha evam Uthaan Mahabhiyaan (PM-KUSUM) program was introduced by the Indian government in 2019. Its component A incentivizes farmers to build solar photovoltaic systems on their property in order to sell power to distribution companies at a predetermined cost. Under component C of the proposal, feeder-level solarization is also covered. This entails mounting solar power plants atop agricultural feeders [9]. The Act intends to accomplish the following: - The installation of 10GW of Decentralized Ground Mounted Grid that Connects with the Renewable Power Plants, with each plant having a maximum capacity of 2MW. A farmer, a group of farmers, a cooperative, or an farmer producer organization (FPO) will use their uncultivated and barren land to establish 500kW and 2MW Renewable Electric Power Projects (REPP) [10].

Table 2. Schemes in India to Promote Agrivoltaics [9]-[11].

Sate/UT	Policy/Scheme	Key Points
New Delhi	Delhi Solar Policy, 2022	The policy promotes the installation of solar on agricultural property using a variety of approaches, such as community solar and group net metering.
Uttar Pradesh	Uttar Pradesh Solar Energy Policy, 2022	All over the State, but especially in the Bundelkhand area, Uttar Pradesh New and Renewable Energy Development Agency (UPNEDA) would generate wastelands and land banks unsuitable for cultivation. With the agreement of the State Nodal Agency, the State will offer a facility for considered land conversion from agricultural to non-agricultural purposes.
Maharashtra	Mukhyamantri Saur Krushi Vahini Yojana and PM KUSUM	In order to develop ground-mounted decentralized solar power projects and provide farmers with electricity throughout the day, a tariff cap of INR 3.05/unit has been granted. (Previously, it was 3.11 per unit as agreed upon by Energy Efficiency Services Limited and Maharashtra State Electricity Distribution Co. Ltd.)
Odisha	PM KUSUM	The Odisha State energy Regulatory Commission has set the KUSUM Scheme's unit pricing for energy produced by decentralized solar PV projects at INR 3.08/-.
Haryana	PM KUSUM	The Electricity Regulatory Commission has authorized a KUSUM (A) plant pricing of INR 3.11 per unit.
Punjab	PM KUSUM	A rate of INR 2.7/unit has been agreed by the Punjab State Electricity Regulatory Commission for SPV plants under KUSUM component A with a capacity of 217 MW.

6. AGRIVOLTAICS IN FISH FARMING AND IRRIGATION IN INDIA

India's agriculture is heavily dependent on irrigation and fish farming due to the country's massive peasant population. To increase productivity and profitability, farmers are increasingly turning to innovative technologies like APV because traditional farming isn't necessarily sustainable. It is a custom of freshwater fish culture in India. India is the world's third-largest fish producer, accounting for 7.96% of total fish output [21]. A research on an APVs that integrated PV panels with fish farming discovered that the shadowing of the solar panels significantly increased fish productivity and enhanced water quality [22]. APVs have been demonstrated by the Indian Council of Agricultural Research (ICAR) to produce solar electricity and enhance crop yields by as much as 30% [23].

7. CONSTRAINTS

7.1 Economic Indicators for APV

In combination with the advancement of economic infrastructure, solar-powered energy generation holds promise for rural electrification and economic prosperity. Two distinct solar energy generating systems a surface-mounted system and uplifted solar system with an agricultural production upon the same ground were examined in terms of their economics. Due to their minimal maintenance costs, these renewable energy sources are perfect for electrifying rural areas. However, the expensive cost of capital and installation is one of the barriers preventing solar-powered energy generation from being widely adopted. To facilitate the idea of dual land use for agricultural and energy production, an economic study of ground-mounted and APVs of equivalent capacity is carried out. The net present value (NPV) method takes rate of return and inflation into account when comparing the present value of money to its future worth. NPV is based on the discounted cash flow method [4].

7.2 Soil Quality

The qualities of soil are greatly impacted by changes in land use. The building of photovoltaic power plants modifies the natural environment, impacting biological activity, soil hydrology, carbon and vegetation dynamics, and other ecological processes. To improve the geographic variability of soil quality within PV array regions and help achieve net-zero emissions by 2050, combining crops with installed PV components to form a "agrivoltaic" ecosystem on vulnerable land may be a potential technique. For instance, the shadowing effect of PV systems can reduce the stress caused by drought for plants in arid areas, increasing food yields. Moreover, incorporating crops with photovoltaic power plants offers a cooperative way to enhance the biological, chemical, and physical characteristics of the soil. The fluctuation of light resources beneath the panels is one of the issues with APV systems. Because of changes in the sun elevation angle, an area of the ground with continuously varying energy inputs is fashioned into a strip thanks to the shadowing created by photovoltaic modules. An increasing degree of geographical variation in soil quality is a result of these intermittent energy inputs [8].

7.3 Agronomic Aspects

APV plant concepts must take into account the cost-conscious Indian energy market in order to be identified. In this regard, growing horticulture and commercial crops—which are more valuable on the Indian market and contribute to increased exports—might be feasible. This may increase an APV project's financial feasibility. Due of their comparatively high commercial worth, vegetables, medicinal plants, spices, and even flowers have been grown beneath the panels in the majority of cases. Growing in popularity in India are bifacial solar panels with translucent backsheets, which should make it possible to plant a greater range of crops beneath the raised structure [10]. The individual botanical makeup of each facility, along with its unique soil and climatic circumstances, may be used to explain the variation in forage dry matter production. Visual observations of the animals' behavior were used to gauge and assess the wellbeing and well-being of the animals. Because the ruminants stayed under the panels throughout the hottest part of the day, their peak activity was reduced. While the general herd cleanliness remained the same, the cows housed under the PV system had much cooler body temperatures throughout the day [3]. “Agrological Value” Map, these criteria are met by the map, which classifies soil fertility according to agrological classifications. PV plants are not suitable for use in agrological classes I and II soils. When no other options exist and a thorough investigation has been conducted to substantiate the claim, photovoltaic plants may be planted on agrological classes III and IV soils with a maximum surface area [5].

7.4 Variations in Microclimate and Their Impact on Crop Production

By lowering greenhouse gas (GHG) emissions associated with agriculture, such as those from pumping and irrigation, which mostly rely on fossil fuels, APVs have the potential to slow down global warming. APVs have the potential to boost land productivity by up to 90%, or roughly 70%. While food and energy production may have less competition for land usage as a result of APVs, there are still serious worries that crop output and quality could be hampered by the shade and microclimate conditions beneath APVs. Crop development can be directly impacted by the microclimatic conditions that lie beneath these APVs, which include elements like air temperature, solar radiation, humidity, wind speed, soil temperature, and moisture. When evaluating the sustainability of APVs in agricultural systems, the impact of shadowing on crop productivity is a significant problem in addition to the influence of microclimate variation. The way plants modify their internal processes to tolerate low light levels determines how shade affects productivity. So far, lettuce, pepper, tomatoes, and cucumbers have been the most commonly investigated crops in agricultural photovoltaics. Lettuce yield was unaffected by ground-mounted PV systems that provided 25% and 50% shade in the spring and summer. Because lettuce can tolerate different levels of shadowing, they came to the conclusion that shading had no discernible effect on yield [12].

7.5 Optimization Towards Better Agri-PV Efficiency

The arrangement of the PV modules causes the shadowing beneath the building to change throughout the day in response to the sun's height. In cereals like wheat, rice, and corn, there is a strong correlation between the harvest index and irradiance. The extent of crop development, magnitude, and time at which shade is applied will all affect the size of the production drop. For example, rice yields can drop by up to 73% under extreme shadowing, whereas incoming radiation can drop by up to 77% under such circumstances. The table 3 above lists the various solar module types that are currently in use together with the tracking angles that affect shading in Indian APV plants.

8. CONCLUSION

However, APV are really just getting a pace in India. Land use issues and the absence of a policy framework is identified and improved according to their present needs. The Indian government has faced these obstacles head-on with a number of initiatives to support agrivoltaics. Additionally, the (Indian Council of Agricultural Research) ICAR has carried out a number of studies to illustrate the advantages of agrivoltaics. These new prospects provide a substantial path for economic growth. APV systems, therefore improving the nation's capacity for renewable energy and creating jobs for people with different skill levels at the same time. APVs significantly increase its contribution to the advancement of environmentally friendly farming and rural growth in India with the correct policies and programs in place.

Table 3. APV shading impacts on agricultural practices and crops [10].

Project Name	Type of APVs	Mounting Structure	Tracking	Shading	Cultivated Crop	Future Aspects
Krishi Vigyan Kendra Ujwa Solar Farm, Delhi	A raised structure with space below for some agricultural	3.5 m above ground with a 15° inclination	Fixed tilt	Minimal Shading	Okra, tomato, brinjal	Over 720 more Krishi Vigyan Kendras were founded in India.
Agrivoltaics plant near Parbhani, Maharashtra	Shadehouse and elevated structure	Overhead 3.75 m with tilt of 11°	Fixed tilt	Shade due to used PVs.	Cherry, Capsicum, Cucumber	January 2023 marked the start of crop cultivation.
Sandhwani Solar Power Plant	Primarily interspace, with some cultivation occurring beneath panels	Panels raised by 2.2 meters	Seasonal tilt	Seasonal Shading	Eggplant, onion, chilly and ladyfinger	Agrivoltaics facility spanning 1.5 acres of land in total
GroSolar Agri-PV Interspace System, Dhule, Maharashtra	Interspace	Elevation of 2m.	Fixed tilt	Due to PVs being employed, there is shade.	Geranium, Guava, Lemongrass	The electricity generated is also utilized to power neighboring village residences and farmers' farming operations.
Sun Master Agri-PV System, Delhi, India	Overhead	Hot Dip Galv	Fixed tilt	PVs Shade	Bottle Guard, Fenugreek	Massive steel structure and foundations
Agritech Innovation Pilot 2.0	Elevated structure	Panel elevation of about 3.5 meters	Fixed tilt	Very minimal Shade.	Multiple, high growing crops possible	Drip watering system Accommodating tractor-driven cultivation

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