Auroville Consulting

ENERGY CO-BENEFITS OF AGRIVOLTAICS SYSTEMS

AN ASSESSMENT FOR INDIA

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EXECUTIVE SUMMARY

Agrivoltaics (AgriPV) presents an innovative solution that combines solar energy generation with agricultural production, enabling dual land use and enhancing land-use efficiency. Its benefits are wide-ranging —contributing to upstream energy benefits for the power network while offering co-benefits such as employment generation, additional income to farmer, rural energy access and energy independence through energy democratisation. This executive summary synthesizes the report's key insights, analytical findings, and policy recommendations.

AgriPV – Current status and potential

Currently, there are 22 operational AgriPV pilot projects across India, varying in size and crop types. These projects offer valuable insights into crop compatibility and the impacts on surrounding ecosystem services. With agricultural land covering approximately 58% of India's landmass, there is significant potential for scaling AgriPV installations. Site selection criteria must ensure optimal energy generation while minimizing environmental impacts. Proximity to electrical infrastructure and road networks is also essential to reduce interconnection and installation costs. Deploying AgriPV systems with compatible crops can enhance financial viability and ease adoption. The availability of suitable agricultural land, coupled with supportive policy and regulatory frameworks across states and UTs, can facilitate early adoption. Providing a combination of financial support— such as subsidies and tax incentives – and capacity-building measures like targeted awareness and training programs is essential to help marginal and small farmers to adopt AgriPV systems effectively.

AgriPV - Upstream Energy benefits

Integrating distributed solar systems into the power network can enhance grid stability and improves power quality. By generating and supplying electricity locally, it significantly reduces transmission and distribution losses typically associated with long-distance power transport. It also enables the deferment of electrical infrastructure investments, as distributed systems like AgriPV reduce the overall load on the grid. These upstream benefits—related to the maintenance and expansion of physical infrastructure—result in substantial cost savings by avoiding expenses linked to contracting demand from the transmission network and increasing generating capacity, as local systems meet energy needs more efficiently.

Moreover, incorporating renewable energy technologies such as AgriPV into the power network supports the transition away from fossil fuel-based electricity generation. While the emission reduction potential of AgriPV systems is similar to other distributed solar systems, AgriPV offers the added advantage of dual land use—simultaneously supporting energy generation and agricultural productivity.

AgriPV – Co-benefits

The adoption and integration of AgriPV systems into the power sector offer several co-benefits beyond energy generation. These systems create employment opportunities, as their installation, operation, and maintenance require skilled labour. This employment potential can contribute to rural development by generating local job opportunities. AgriPV also supports emission reduction, which in turn improves public health by reducing exposure to harmful pollutants such as sulphur dioxide, nitrogen oxides, and particulate matter typically released by fossil fuel-based power plants.

Additionally, AgriPV promotes energy democratisation by empowering farmers to generate, consume, and supply electricity, thereby enhancing both energy access and energy independence. AgriPV systems offer farmers the opportunity to earn extra income by selling generated electricity to the grid. Compared to fossil fuel-based thermal plants, AgriPV systems consume significantly less water over their operational lifespan and result in lower soil contamination and waste generation. These characteristics position AgriPV as a sustainable and environmentally friendly solution for long-term clean energy generation.

AgriPV – Policy and Regulatory framework

The policy and regulatory framework for AgriPV is currently shaped by a range of existing policies related to electricity generation, grid interconnection, agriculture, land use, and environmental safeguards. However, the absence of a unified and standardized AgriPV policy leads to regulatory ambiguity, posing significant adoption challenges—particularly for marginal and small farmers. Limited financial support and complex interconnection requirements further hinder their ability to implement AgriPV systems. Additionally, the need to reclassify agricultural land for AgriPV installations often disqualifies farmers from accessing critical agricultural subsidies, which are essential for their livelihood. To enhance adoption and build social acceptance, it is crucial to provide regulatory clarity, targeted financial support, and farmer training through dedicated capacity-building initiatives.

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Agrivoltaics	AgriPV
Biennial Update Report	BUR
Business-as-usual	BAU
Capacity Utilisation Factor	CUF
Carbon-di-oxide	CO2
Commercial and Industrial	C&I
Distributed Energy Resources	DER
Distribution companies	DISCOMS
Environmental and Social Impact Assessments	ESIA
Environmental Systems Research Institute, Inc	ESRI
Farmer Producer Organisation	FPO
Feed-in tariff	FiT
Full-time equivalent	FTE
Giga-tonne	Gt
Giga-tonne Carbon-di-oxide	GtCO2
Giga-watt	GW
Global Horizontal Irradiation	GHI
Greenhouse Gases	GHG
Gross Domestic Product	GDP
Gross Value Added	GVA
Hectare	ha
Kilo-gram	kg
Kilo-volt	kV
Kilo-watt-hour	kWh
Land Use	LU
Land use and Land change	LULC
Land Use, Land-Use Change, and Forestry	LULCCF
Mega-tonne carbon-di-oxide equivalent	MtCO2e
Methane	CH4
Million Tonnes	MT
National Highway	NH
Nationally Determined Contribution	NDC
Nitrous Oxide	NO2
Particulate Matter - 10	PM10
Particulate Matter - 2.5	PM2.5
Peer-to-peer	P2P
Photovoltaics	PV
Power Purchase Agreement	PPA
Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan	PM KUSUM
Proceedings of the National Academy of Sciences	PNAS
Relative Shade Rate	RSR
Renewable Energy	RE
Renewable Purchase Obligation	RPO
Second National Communication	SNC
Social cost of Carbon	SCC
Spheroidal carbonaceous particle	SCP
State Highway	SH
Sulfur oxides	SO2
Sustainable Development Goals	SDGs
Terra-watt hours	TWh
Terra-watt peak	TWp
Tertiary Roads	TR
Third National Communication	TNC
Transmission and Distribution	T&D
Union Territories	UTs
Value of Distributed Energy Resources	VoDER

1.0. INTRODUCTION

As India's food and energy demands grow amid climate challenges, Agrivoltaics (AgriPV) systems offer a sustainable solution by enabling dual land use for agriculture and solar power, enhancing food security, energy transition, rural livelihoods, and environmental resilience, while requiring supportive policies for wider adoption.

As the global population approaches 9.7 billion by 2050, the demand for food and energy is expected to rise, increasing pressure on natural resources amid ongoing climate change (UN DESA, 2021). Globally agriculture faces challenges due to shifting weather patterns, rising temperatures, and resource constraints (IPCC, 2021). Approximately 50% of India's cultivated land is rainfed, making it sensitive to monsoon variability, which can affect crop yields and farmer incomes (NABARD, 2022). Research suggests that a global temperature increase beyond 1.5°C could lead to more frequent and prolonged droughts, with potential implications for food production (IPCC, 2021).

In India, agriculture contributed 18% to the Gross Value Added (GVA) in 2022-23 and employs approximately 43% of the workforce in agriculture and allied sectors (MoAFW, 2024; World Bank, 2024). According to the Ministry of Agriculture and Farmers Welfare (MoAFW), agricultural land and permanent pastures account for nearly ~60% of India's total land use (MoAFW, 2024).

Table 1 – India land cover – Land use statistics 2022-23

LAND CLASSIFICATION	AREA ('000 HECTARE)	% OF AREA
Forests	72,021	23.49%
Area put to non-agricultural uses	27,845	9.08%
Barren & unculturable land	16,554	5.40%
Permanent pastures & other grazing	10,248	3.34%
Agricultural Land	1,79,982	58.69%
Reporting area	3,06,650	100.00%

Source: MoAFW 2024

India's energy demand is projected to grow significantly, increasing its share of global energy consumption from 5% to 11% by 2040 (IEA, 2017). With India accounting for 6.65% of the global total emissions, the transition to renewable energy (RE) remains a priority (IEA, 2021). The country has set a target of 500 GW of non-fossil fuel capacity by 2030. In 2030 solar energy is expected to make up 280 GW, or around 56% of the 500 GW of non-fossil fuel capacity target. Currently, the country's installed RE capacity stands at 214.67 GW, with solar energy contributing 47% of the current RE capacity (MNRE, 2024). Large-scale solar farms are the current go-to option to meet the 2030 solar target. The expansion of large-scale solar farms has raised land-use concerns, as agricultural land is frequently repurposed for energy projects (Supe et. al., 2024). By 2050, solar energy is estimated to require approximately 2.84% of India's total land area (IEEFA, 2021). A significant portion of the solar energy development to date has occurred on agricultural and natural land rather than wastelands, affecting rural livelihoods and land availability for farming (Supe et. al., 2024). This has led to the development of alternative solar deployment options with neutral or negligible land-use impact, such as AgriPV.

AgriPV systems, introduced by Goetzberger and Zastrow in 1982 (Weselek et al., 2019), enable simultaneous land use for agriculture and solar power generation (Dupraz et al., 2011). They address land-use conflicts while supporting food and energy security, aligning with Sustainable Development Goals (SDGs) 2 – Zero Hunger, 7 – Affordable and Clean Energy, 11 – Sustainable cities and communities, and 13 – Climate Action (Ghosh, 2023). AgriPV offers operational, environmental and economic benefits, such as reducing water evaporation by 14%-47% (Lopez-Garcia et al., 2024; Soto-Gómez, 2024; Weselek et al., 2019) and contributing to slight increase in panel efficiency (Soto-Gómez, 2024). It diversifies farmer income, supports rural electrification, and generates employment (Ghosh, 2023). While solar PV applications, including AgriPV, are a low-emission energy source, their impact on ecosystem services and biodiversity requires further study (Gómez et al., 2024, GIZ, 2025).

The following chapters explore the potential of AgriPV in India and its energy and other co-benefits such as emission reduction, employment generation, and increasing energy democratisation. Chapter 2 assesses India's AgriPV's potential. Chapter 3 examines its role in emissions reduction and decarbonisation. Chapter 4 discusses employment generation and economic benefits for rural communities. Chapter 5 highlights the upstream energy benefits of integrating AgriPV in power network. Chapter 6 adds on the co-benefits of AgriPV systems. Chapter 7 identifies the gaps in existing policy and regulatory framework and provide recommendations. Chapter 8 provides a potential roadmap for AgriPV. Chapter 9 summarizes key insights and actionable recommendations.

2.0. AGRIPV POTENTIAL IN INDIA

India has immense AgriPV potential, with just 1% of arable land capable of accommodating 800 GW of AgriPV capacity, but effective deployment requires strategic land selection, regulatory support, and financial viability to maximize energy generation, crop yields, and rural economic benefits.

With approximately 170 million hectares under cultivation, India has significant potential for solar energy, with approximately 1 million hectares of land required to achieve the target of 280 GW by 2030 (Supe et. al., 2024). Effective deployment requires careful land selection to minimise ecological impact while maximizing energy generation and crop yields. This chapter estimates India's AgriPV potential while considering environmental, technical and commercial constraints.

Global case studies demonstrate AgriPV's viability across diverse climatic and geographic conditions, supporting decarbonization, water conservation, and rural economic growth. Table 2 provides few of the global estimates for AgriPV. AgriPV presents a significant opportunity to optimize land use and enhance farmer incomes (Mahto et al., 2021; IEEFA, 2021; NSEFI, 2023). India's high solar radiation (3.5–7 kWh/m²/day) and ~3,000 annual sunshine hours create ideal conditions for AgriPV deployment (Gadhiya & Patel, 2023; Jain et al., 2024).

Various studies estimate India's AgriPV potential. Crop-specific assessments suggest a large potential between 3,156 GW and 13,803 GW (CSTEP, 2024). Another study estimated the potential for AgriPV on different land categories assuming 1% coverage; utilising arable land could provide a potential of 814 GW while covering only fallow land could provide a potential of 118 GW. (NSEFI, 2023). Drylands are areas characterized by low rainfall, high evaporation rates, and water scarcity, making them less suitable for conventional agriculture but ideal for AgriPV due to abundant sunlight. As of 2024 over 22 AgriPV projects are operational, with pilot studies reporting a substantial increase in farmer incomes, alongside rural job creation and economic stability.

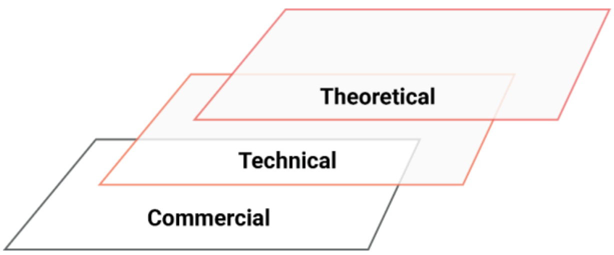
Table 2 – Estimated AgriPV potential of multiple countries

Country	AgriPV potential	References
European Union	944 GW	(Chatzipanagi, 2023)
Czechia, Hungary, Poland, and Slovakia	180 GW	(Czyzak & Mindekova, 2024)
Germany	215 GW	(Rosch & Fakharizadehshirazi, 2024)
Japan	231 GW	(Sekiyama & Nagashima, 2019; Ghosh, 2023)
Qatar	4 GW	(Lopez-Garcia et al., 2024)
South Africa	193 GW	(Brent et al., 2024)
Canada	163 GW	(Jamil et al., 2023)

2.1. Methodology

This section outlines the methodology used to estimate the AgriPV potential in India. According to India's 2022-23 Land Use Statistics, cultivated land accounts for 50% of the total land area, including net sown and current fallow land. Expanding this to include other fallow land increases the cultivated land share to 58% (MoAFW, 2024). Publicly available Geographic Information System (GIS) data and 2023 land use and land change (LULC) data were used to identify cropland, which includes land for annual and perennial crops but excludes tree crops, permanent pastures, and shifting cultivation.

Figure 1 – Methodology to estimate the AgriPV potential



To refine the estimation, multiple constraints were applied to identify cropland suitable for AgriPV. Given ongoing research on AgriPV's ecological impact, a minimum buffer from forests and water bodies was included as a selection criterion to minimize potential disruptions to biodiversity, protect sensitive ecosystems, and ensure sustainable land use practices. Technical factors such as Global Horizontal Irradiance (GHI), slope, and tilt angle were also considered. Additionally, proximity to the electrical substation and road access was factored in, as longer distances increase interconnection and logistical costs. A structured three-step process incorporating theoretical, technical and commercial constraints was used to identify suitable cropland for AgriPV. The methodology is illustrated in the figure 1.

2.1.1. Theoretical potential

The theoretical assessment focused on identifying cropland in India suitable for AgriPV deployment. Using Environmental System Research Institute, Inc. (ESRI) Sentinal-2, 10m Land Use/Land Change by ESRI and Impact Observatory – 2023 (ESRI, 2023), the total cropland was estimated at 167 million hectares, which represents the theoretical AgriPV potential**.** The resolution was adjusted to 1,000 meters, resulting in an estimated accuracy of approximately 90–95%. State and Union Territory (UT) level analysis showed Uttar Pradesh (20.4 million ha) and Maharashtra (20.1 million ha) as having the highest cropland areas. Table 3 has the details of ten states with the largest share of available cropland in India, collectively accounting for 134 million hectares—indicating a strong concentration of cropland in few regions.

Figure 2 – Cropland available under theoretical potential for AgriPV, identified from GIS data

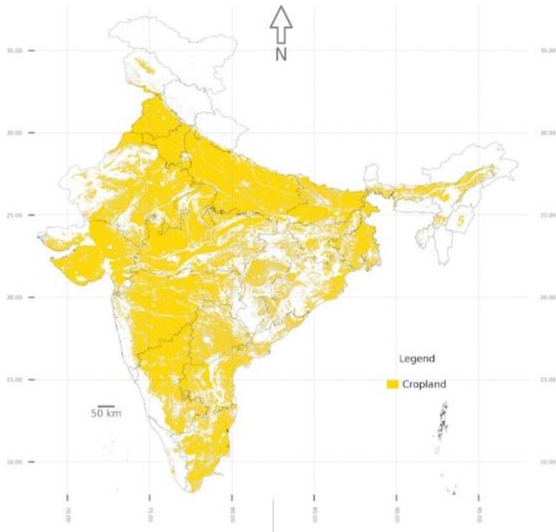


Table 3 – Ten states with the largest share of total available cropland in India

State	% share of Cropland
Uttar Pradesh	12.20%
Maharashtra	11.99%
Madhya Pradesh	11.59%
Rajasthan	10.68%
Gujarat	7.49%
Karnataka	7.32%
Andhra Pradesh	5.29%
Tamil Nadu	4.79%
Bihar	4.43%
Telangana	4.32%

2.1.2. Technical potential

To identify cropland with technical potential for AgriPV deployment, a spatial assessment was conducted using criteria that support optimal solar energy generation while minimizing ecological impact. The analysis incorporated technical parameters such as terrain suitability - slope, solar radiation levels, and proximity to sensitive ecosystems – forest and water.

2.1.2.1. Slope

A Digital Elevation Model (DEM) of India was sourced from publicly available datasets (Sandwell et al., 2016) to calculate land slope (%). The Indian landmass was divided into seven latitude-based zones, each assigned a representative slope value to reflect optimal south-facing tilt angles, aiming to minimize construction complexity.

Table 4 – Indian landmass divided into seven layers according to latitude and representative slope (%) values

Section	Latitude range (deg.)	Slope in %
Layer#1	41.47 – 36.47	74 %
Layer#2	36.47 – 31.47	61 %
Layer#3	31.47 – 26.47	50 %
Layer#4	26.47 – 21.47	39 %
Layer#5	21.47 – 16.47	30 %
Layer#6	16.47 – 11.47	20 %
Layer#7	11.47 – 6.47	11 %

This approach enables the consideration of different slope (%) values for each zone. However, it is important to acknowledge that intra-zone slope variations exist within each zone and using a single representative slope value is a broad approximation. Despite this limitation, the identified slope value is used to estimate feasible cropland within each section.

2.1.2.2. Global Horizontal Irradiance (GHI)

Global Horizontal Irradiance (GHI) data, also obtained from open-source GIS platforms (GSA, 2019) was used to assess solar resource availability. A minimum GHI threshold of 3.60 kWh/m²/day was applied to ensure inclusion of areas in northern and north-eastern India with relatively lower solar radiation. GHI values vary significantly across India—from 5.50–6.00 kWh/m²/day in the northwest and central regions to 3.00–4.00 kWh/m²/day in the northeast—due to geographic and climatic differences. This threshold ensures a comprehensive evaluation across diverse solar zones.

2.1.2.3. Distance from forest cover and water body

To reduce ecological impacts, a buffer of 500 meters was applied around forests and water bodies, excluding cropland within this range from AgriPV consideration. This constraint aims to prevent habitat fragmentation, safeguard biodiversity, and protect water systems. Proximity to forests can disrupt microclimates and increase deforestation risk, while installations near water bodies may affect water quality and aquatic ecosystems. All spatial layers—including cropland, forest cover, and water bodies—were derived from a consistent GIS dataset to maintain methodological coherence. This integrated approach ensures that land identified for AgriPV development meets both technical feasibility and environmental sustainability criteria.

2.1.3. Commercial potential

Commercial constraints were defined based on their influence on the financial viability of the AgriPV systems. A primary barrier to AgriPV adoption is the substantial upfront investment required for components such as solar infrastructure, land development, power evacuation infrastructure, and modifications to existing irrigation systems. To define suitable commercial constraints, two parameters, distance from the road network and distance from the electrical substation, were utilized. The detailed composition of the two-parameter sets is presented below.

2.1.3.1. Distance from road network

Access to the road network plays a critical role in the construction, installation, and ongoing maintenance of AgriPV systems. The road network data has been taken from Open Street Map. For this analysis, the road network was classified into three categories:

- National Highways (NH): Primary arterial routes that enable the efficient movement of heavy machinery and construction materials.
- State Highways (SH): Secondary routes connecting districts and regions, offering access to semi-urban and rural agricultural areas.
- Tertiary Roads (TR): Local/Minor roads that provide direct connectivity between small towns or rural areas to larger roads.

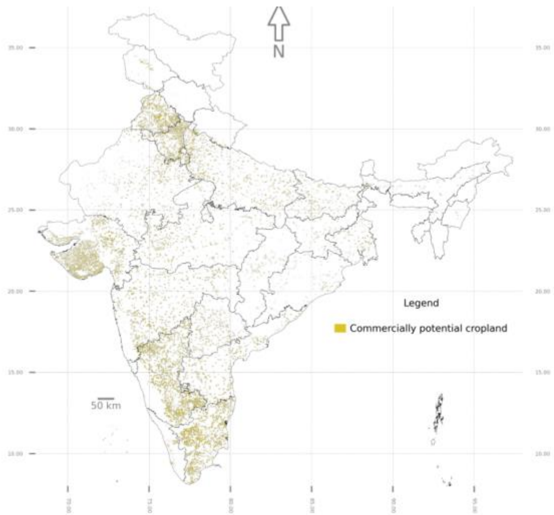
Reliable road access contributes to reduced logistics costs, facilitates workforce movement, and ensures timely delivery of solar components and agricultural inputs. Furthermore, improved connectivity strengthens farmers' access to markets, enhancing the commercial viability of AgriPV systems. Consequently, a maximum distance of 500 meters from the road network was applied as a constraint in the site selection process.

2.1.3.2. Distance from electrical substation

Proximity to grid infrastructure allows for efficient solar power evacuation, minimizing transmission losses and lowering capital costs. Proximity to electrical substations is particularly significant under regulatory frameworks such as the PM-KUSUM Scheme, which incentivizes decentralized solar installations. Under Component A of the scheme, solar plants with capacities up to 2 MW must be located within 5,000 meters of an existing substation to be eligible for participation.

Distance from electrical substations also affects the ease of obtaining regulatory clearances and acquiring land. Long-distance distribution lines may require additional approvals—such as environmental clearances and land-use permissions—as well as coordination with State Electricity Regulatory Commissions (SERCs). Maintaining proximity to distribution infrastructure simplifies these processes, reducing compliance risks and project delays. Accordingly, this study incorporates proximity to the substation as a critical constraint for the commercial viability of AgriPV projects.

Figure 3 – Cropland with commercial potential identified through GIS analysis



2.2. Result: Available cropland for AgriPV

According to Land Use (LU) Statistics for 2022–23, India's total reported cultivated area stands at 165 million hectares. However, GIS-based analysis of Land Use and Land Cover (LULC) data estimates total cropland at approximately 167 million hectares. For this study, the GIS-derived cropland dataset has been used, as it offers a spatially detailed and consistent foundation for assessing AgriPV feasibility. Table 5 outlines the extent of cropland available after successive filtering through theoretical, technical, and commercial constraints. These refinements allow for a more accurate assessment of land suitability for AgriPV deployment.

Table 5 – Theoretical, Technical and Commercial AgriPV Potential for India

Layers	Available cropland (million hectare)	% change
Theoretical	167.736	100.00%
Technical	162.596	96.93%
Commercial	16.586	9.89%

Approximately 80% of the commercially feasible cropland is concentrated in just ten states, Table 6 Provides details of the ten states with the largest share of theoretical and commercially available cropland relative to India's total cropland under theoretical and commercial potential respectively, presented both as a percentage and in million hectares. This highlights the availability of suitable land for AgriPV after applying the constraints to India's total cropland (theoretical potential).

Table 6 – Ten states with respective percent share of cropland available under theoretical potential and commercial potential relative to India's total cropland available under theoretical potential and commercial potential for AgriPV

State	India's cropland with theoretical potential by state		India's cropland with commercial potential by state	
	% share	Million hectare	% share	Million hectare
Andhra Pradesh	5.29%	8.87	4.97%	0.82
Bihar	4.43%	7.44	2.08%	0.34
Gujarat	7.49%	12.56	14.71%	2.44
Karnataka	7.32%	12.27	18.50%	3.07

Madhya Pradesh	11.59%	19.45	4.71%	0.78
Maharashtra	11.99%	20.12	8.55%	1.42
Rajasthan	10.68%	17.91	5.16%	0.86
Tamil Nadu	4.79%	8.04	13.78%	2.29
Telangana	4.32%	7.25	3.41%	0.57
Uttar Pradesh	12.20%	20.47	6.96%	1.15

Figure 4 – Available cropland under theoretical and commercial potential using GIS analysis

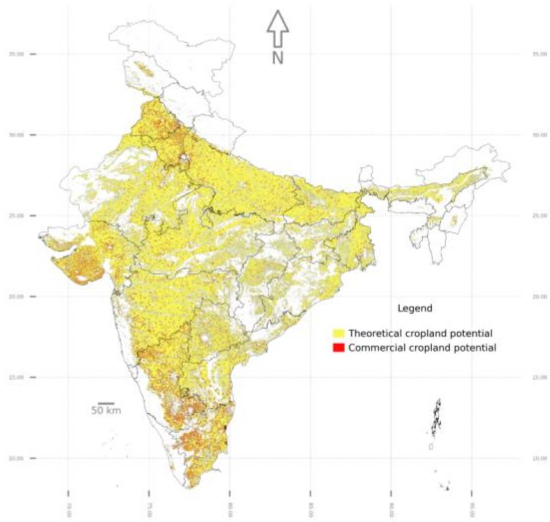


Table 7 – Ten states and UT with the largest share of commercial cropland available as compared to their respective state's theoretical cropland potential

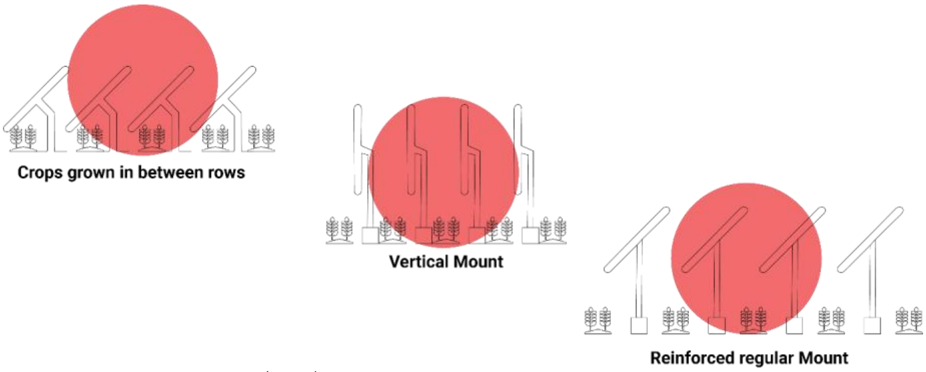
State	% share of commercially available cropland	Commercially available cropland (million hectare)
Chandigarh	69.05%	0.002
Delhi	52.39%	0.035
Goa	45.20%	0.005
Kerala	43.47%	0.087
Puducherry	39.70%	0.021
Tamil Nadu	28.44%	2.286
Karnataka	24.99%	3.068
Dadra & Nagar Haveli And Daman & Diu	21.10%	0.005
Punjab	20.19%	0.945
Gujarat	19.43%	2.440

Table 7 Provides details of the ten states and UT with the largest share of commercially available cropland relative to the respective state's theoretical cropland potential. Identifying high-potential states can aid in formulating targeted policies, offering financial incentives, and infrastructure planning to accelerate AgriPV adoption. Focusing on these states can help optimise regulatory framework and investment strategies, enabling initial deployment and implementation of AgriPV.

2.3. Crop types and AgriPV configurations

The suitability of crops for AgriPV systems depends on their shade tolerance and the configuration of the photovoltaic installation, which directly affects light availability. Crops can be grouped based on their relative shade rate (RSR) tolerance (Anamalagundam et. al., 2023). Shade-tolerant crops, with an RSR of less than 35%, such as leafy vegetables like spinach and lettuce, and root crops like carrots and radish, can grow well under reduced irradiance, benefiting from improved microclimatic conditions and lower water evaporation. Moderately shade-tolerant crops, with RSR below 25%, including tomatoes, peppers, potatoes, and certain cereals, require partial sunlight and are compatible with structured AgriPV systems that optimize light penetration. In contrast, sun-loving crops, requiring less than 10–15% RSR, such as corn, rice, and sunflowers, demand high solar exposure and are generally unsuitable for densely installed AgriPV systems unless specific design modifications are made to enhance light access.

Figure 5 – Various configurations for AgriPV considered in the study – Interspaced, Vertical and Overhead



Source - SolarPower Europe (2024)

The configuration and panel density of AgriPV systems play a significant role in determining crop performance. Overhead AgriPV (regular mounted) systems, where panels are elevated above the ground, enable uniform light distribution and allow space for mechanized farming. This configuration is well-suited to shade-tolerant and moderately shade-tolerant crops. While denser panel arrangements in overhead systems may reduce sunlight, they contribute to better soil moisture retention and temperature regulation. Interspaced AgriPV systems, which feature widely spaced panel rows, offer a more balanced approach by ensuring sufficient sunlight for crops while maintaining solar energy generation, particularly benefiting crops with moderate shade tolerance. Vertical AgriPV systems, with panels arranged at steep angles or in vertical alignment, minimize shading on crops, making them more appropriate for sun-loving varieties. Though this setup maximizes land-use efficiency, it may require adjustments in crop spacing or planting density to maintain optimal light exposure (SolarPower Europe 2024).

Integrating crop selection with system design is critical to achieving dual benefits of energy production and agricultural productivity. By strategically choosing AgriPV configurations and optimizing panel placement and density, shading effects can be mitigated, enabling diverse cropping patterns while maintaining the economic viability and sustainability of the system.

Table 8 outlines various crop types (MoAFW, 2024) along with their corresponding relative shade rates. Based on these values, appropriate AgriPV system configurations and panel densities (CSTEP 2024, SolarPower Europe 2024) were selected to minimize potential yield losses. Using this approach, the commercially available cropland in each state and UT was assessed for available crop types, enabling an estimation of the AgriPV potential based on crop type and suitable AgriPV configuration across different states and UTs.

Table 8 – Crop types with corresponding relative shade rates, along with suitable AgriPV configurations and panel densities

Crop types	Configuration	Shade tolerant - (RSR - Relative shade rate)		Density (kWp/ha)
Cereals	Vertical and sparse	Low shade-tolerant	<15 - 10% RSR	250-300
Pulses	Overhead/Vertical	Moderately shade-tolerant	<25% RSR	300-400
Sugar	Overhead and sparse	Low shade-tolerant	<10%	150-250
Condiments and Spices	Overhead	Shade-tolerant crops	<35%	650-750
Fresh fruits	Overhead	Moderately shade-tolerant	<25% RSR	300-400
Dry fruits	Overhead	Low shade-tolerant	<15 - 10% RSR	150-250
Vegetables	Overhead/interspaced	Shade-tolerant crops	<35%	650-750
Other food crops	Overhead/interspaced	Low shade-tolerant	<10%	250-300
Oilseeds	Overhead	Moderately shade-tolerant	<25% RSR	300-400
Fibres	Overhead	Shade-tolerant crops	<35%	650-750
Dye and Tanning	Overhead/interspaced	Moderately shade-tolerant	<25% RSR	300-400
Drugs narcotics and other plantation	Overhead	Moderately shade-tolerant	<25% RSR	300-400
Fodder	Overhead/interspaced	Moderately shade intolerant	<25% RSR	300-400

Source: Anamalagundam et. al., 2023, CSTEP 2024, SolarPower Europe 2024, MoAFW, 2024

2.4. Deployment scenarios

This section presents the proposed deployment scenarios for AgriPV installations across India, developed based on key parameters such as cropland availability from GIS-based analysis, crop suitability in terms of shade tolerance, and the concentration of feasible cropland in specific states. These factors have been used to develop a virtual deployment scenario for AgriPV. This scenario does not consider demand and grid integration constraints. Each deployment scenario is structured with a target horizon up to 2030, assuming full realization of the estimated AgriPV capacity by 2030. The accompanying table provides a detailed overview of each deployment scenario, including the underlying assumptions and criteria used for capacity projections and assessing implementation feasibility.

Table 9 – Deployment scenarios considered for AgriPV installations until 2030

Deployment scenarios	Description
Theoretical potential scenario	Considering all available cropland under theoretical potential, AgriPV capacity will be determined.
Commercial potential scenario	Considering all available cropland under commercial potential, AgriPV capacity will be determined.
Commercial potential scenario – feasible crop types	Considering all available cropland under commercial potential, AgriPV capacity will be determined only for feasible shade-tolerant crops.
Commercial potential scenario – feasible crop types + States	Considering top ten states with largest share of available cropland under commercial potential, AgriPV capacity will be determined only for feasible shade-tolerant crops

Note: Feasible shade-tolerant crops – Cereals, Pulses, Condiments & spices, Fresh fruits, Vegetables and Fodder; Please refer to Table 6 for the top ten largest states with available cropland under commercial potential.

Table 10 provides the estimated power generation capacity of AgriPV under each of the above-mentioned deployment scenarios.

Table 10 – Potential AgriPV generation capacity (TWp) under each deployment scenario

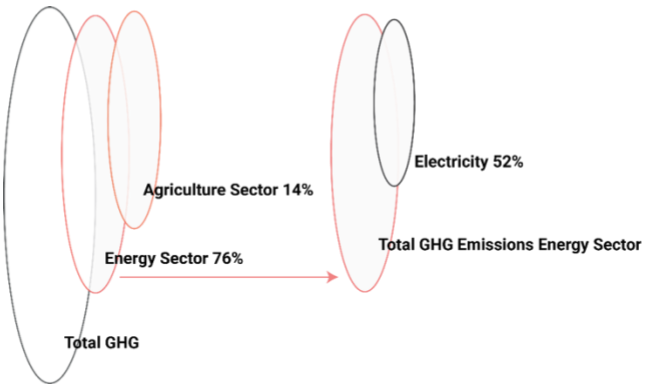
Deployment scenarios	AgriPV potential (TWp)
Theoretical potential scenario	65.06
Commercial potential scenario	6.43
Commercial potential scenario – feasible crop types	4.78
Commercial potential scenario – feasible crop types + States	3.89

3.0. EMISSION REDUCTION POTENTIAL

India aims to achieve developed nation status by 2047 while reducing its GDP emission intensity by 45% from 2005 levels by 2030, yet fossil fuels still dominate its energy mix, making renewable energy expansion—particularly AgriPV—a key strategy for lowering greenhouse gas emissions and enhancing energy security.

India, expected to become the world's third-largest economy by 2028 (IEA, 2024), remains one of the top greenhouse gas (GHG) emitters globally, driven by rapid industrialization and growing energy demand. In alignment with its Nationally Determined Contributions (NDCs) under the Paris Agreement, India has committed to reducing the emission intensity of its Gross Domestic Product (GDP) by 45% from 2005 levels by 2030 (MoEFCC, 2024). As of now, India has installed 215 GW of non-fossil fuel energy capacity and achieved a 36% reduction in GDP emission intensity between 2005 and 2020, signalling meaningful progress toward its 2030 climate goals (MoEFCC, 2024).

Figure 6 – Breakdown of GHG emissions in India: Sectoral contributions from energy and agriculture, with electricity generation's share in energy sector emissions



Source: Niti Aayog, 2025

Nevertheless, the Energy sector accounts for approximately ~76% of total GHG emissions of India, while agriculture contributes approximately ~14%, mainly through methane (CH_4) emissions from livestock and nitrous oxide (N_2O) emissions from fertilizer use (Niti Aayog, 2025, MoEFCC, 2024, BEE, 2024). India is currently the second-largest importer of coal globally, with imports rising to 265 million tonnes (MT) in 2023–24—a 10% increase from 241 MT in the previous year (BEE, 2024). Similarly, oil consumption reached 233 million tonnes in 2023–24, placing India as the third-largest oil consumer worldwide (BEE, 2024).

Table 11 provides a breakdown of historical GHG emissions and removals across sectors. In response to rising energy demands and climate concerns, India is intensifying its push toward RE expansion, aiming to reduce emissions while enhancing energy security.

Table 11 – Greenhouse Gas emissions for India from 1994 – 2020

Year	1994	2000	2007	2010	2014	2016	2017	2018	2019	2020
	MtCO2e									
Sector/ Data source	INC	SNC	SNC	BUR1	BUR2	BUR3	TNC	TNC	TNC	BUR4
Energy	744	1,027	1,374	1,510	1,910	2,129	2,204	2,344	2,374	2,238
Industrial processes and 0roduct use	103	89	142	172	202	226	244	263	264	239
Agriculture	344	356	373	390	417	408	411	417	421	406
LULUCF	14	-223	-177	-253	-301	-308	-312	-437	-485	-522
Waste	23	53	58	65	78	75	70	72	73	76
Total (without LULUCF)	1,214	1,524	1,947	2,137	2,607	2,839	2,929	3,096	3,132	2,959
Total (with LULUCF)	1,229	1,301	1,772	1,884	2,306	2,531	2,617	2,659	2,647	2,437

Note: LULUCF – Land Use, Land-Use Change, and Forestry; SNC – Second National Communication; TNC – Third National Communication; BUR - Biennial Update Report

Source: MoEFCC- India BUR 4, Sector-wise National GHG emission in MtCO2e for 1994-2020

AgriPV is emerging as a promising approach to scale up renewable energy while maintaining agricultural output. Studies suggest that AgriPV can play a substantial role in lowering GHG emissions, improving land-use efficiency, and advancing India's climate goals (Chatzipanagi et al., 2023). This section examines AgriPV's potential in climate mitigation, highlighting its contributions to GHG reduction, renewable energy development, and broader sustainability outcomes.

3.1. Greenhouse Gas (GHG) emissions – Energy sector

India's energy sector is the largest source of GHG emissions, contributing 2.24 giga-tonnes (Gt) of CO_2 equivalent in 2020, with electricity generation accounting for approximately 52% of total emissions (Niti Aayog, 2025). Coal-fired power plants remain the primary emitters within the sector, and coal-based electricity generation is expected to rise by 15% by 2030 (MoSPI, 2024). In response, the government is enacting policies aimed at reducing reliance on coal and accelerating the integration of RE into the energy mix (MoSPI, 2024). By 2029–30, CO_2 emissions from the power sector are projected to reach 1,114 million tonnes (MT), while the average grid emission factor is expected to decline to 0.477 kg CO_2/kWh_{net}—down from 0.727 kg CO_2/kWh in 2024 (CEA, 2023; CEA, 2024). This trend reflects ongoing efforts to decarbonize electricity generation, with new capacity additions becoming increasingly cleaner despite coal's continued presence. Rapid RE deployment is critical for curbing GHG emissions from the power sector, underscoring the need for continued policy innovation, financial support, and technological progress to meet its 2030 targets.

3.2. Greenhouse Gas (GHG) emissions – Agricultural sector

India's agricultural sector is set to expand significantly to meet the food demands of a projected 1.5 billion people by 2030. However, this growth brings concerns about increasing GHG emissions, particularly if sustainable practices are not widely adopted. Efforts to boost crop yields are likely to drive up fertilizer use, contributing to higher nitrous oxide emissions. Simultaneously, increased mechanization may lead to greater dependence on fossil fuel-powered equipment unless cleaner energy alternatives are introduced.

Currently, agriculture contributes ~ 14% of India's total GHG (~ 0.406 $GtCO_2e$) emissions. The primary sources include methane emissions from livestock (54.84%) and rice cultivation (16.68%), as well as nitrous oxide emissions from synthetic fertilizers and soil management (23.26%) (MoEFCC, 2024). Additional emissions stem from diesel-based irrigation, fertilizer application, and land-use changes (Dinesh & Pearce, 2016). Addressing these emissions is critical for meeting national climate goals.

3.3. Renewable energy as a mitigation strategy

Expanding energy access is vital for rural development, yet persistent gaps continue to limit economic growth. The agricultural sector, which accounts for 17% of India's total electricity consumption, is steadily moving toward electrification, with 97% of its energy needs now met through electricity (BEE, 2024). As part of efforts to eliminate diesel use, the number of electrified pump sets has increased by 44% over the past decade, and solar pump installations have grown 45-fold—largely due to government programs like PM-KUSUM, which targets the replacement of 8 million diesel pumps with solar-powered ones, potentially avoiding 32 million tonnes of CO_2 emissions annually.

While solar irrigation provides immediate emission reductions, AgriPV offers a more integrated and long-term solution by combining solar power generation with agricultural activity. With India's expansive agricultural landscape, scaling up AgriPV could significantly boost renewable energy capacity while preserving agricultural output. The next section examines AgriPV's contribution to climate mitigation and GHG reduction, positioning it as a strategic pathway toward a low-carbon, resilient agricultural sector.

3.4. Estimating avoided GHG emissions – AgriPV

As outlined in Section 3.1, the combined margin grid emission factor for the year 2024 is 0.757 $kgCO_2$/kWh. However, to calculate the emission reduction potential of a renewable energy project, a combination of the Build Margin (*which represents emissions from new generation capacity*) and the Operating Margin (*which represents emissions from existing power plants*) is used—this is referred to as the Combined Margin (UNFCCC, 2015). The combined margin for Indian grid is estimated to be 0.757 kgCO2/kWh (CEA, 2025). Utilizing this value, the study assesses the potential avoided emissions under various AgriPV deployment scenarios discussed in Section 2.4. Table 12 presents the projected AgriPV installations for each scenario, along with their estimated annual energy generation. Since AgriPV-generated electricity would displace conventional grid-based power, the previously stated Combined Margin emission factor will be applied to quantify the GHG emissions avoided across different deployment scenarios.

Table 12 – Potential AgriPV installation under the various scenarios, along with corresponding estimated generation, comparison to 2030 electricity consumption and avoided emissions

Deployment scenarios	AgriPV potential (TWp)	Estimated generation (TWh)	Ratio of estimated generation to 2030 electricity consumption	Avoided GHG emissions ($GtCO_2$/year)
Theoretical potential scenario	65.06	1,02,586.61	50.25	77.66
Commercial potential scenario	6.43	10,138.82	4.97	7.68

Commercial potential scenario – feasible crop types	4.78	7,537.10	3.69	5.71
Commercial potential scenario – States + feasible crop types	3.89	6,133.75	3.00	4.64

Note: CUF of 18% is assumed to determine the generation
Source: Total electricity consumption - 2030 – (CEA, 2022)

The Central Electricity Authority (CEA 2022) estimates India's electricity consumption to be 2,041.64 Terawatt-hours (TWh) by 2030. The electricity generation potential of the proposed AgriPV deployment scenarios significantly exceeds this demand. For example, under the Commercial Potential Scenario – States + Feasible Crop Types, electricity generation could reach 6,133 TWh, which is more than 3 times the projected consumption for 2030.

The avoided emissions from the above deployment scenarios surpass India's total 2020 GHG gross emission (without LULUCF) considerably. Avoided GHG emissions from Commercial potential scenario – States + feasible crop types – is 1.5 times more than the total GHG emission of the country as reported in 2020 – refer to Table 11. This highlights the substantial mitigation potential of AgriPV while leveraging the dual advantage of agricultural land use. However, careful assessment is essential to prevent adverse ecological and environmental impacts associated with large-scale installations.

Table 13 – Estimated AgriPV installation for states with the largest available cropland under the theoretical potential scenario, along with corresponding estimated generation, comparison to 2030 electricity consumption and avoided emissions

States	AgriPV potential (TWp)	Estimated generation (TWh)	Ratio of estimated generation to 2030 electricity consumption	Avoided GHG emissions ($GtCO_2$/year)
Andhra Pradesh	3.68	58,02,624	50.12	4.39
Bihar	2.50	39,42,000	62.21	2.98
Gujarat	5.57	87,82,776	43.12	6.65
Karnataka	5.03	79,31,304	87.59	6.00
Madhya Pradesh	2.57	1,13,37,192	85.37	8.58
Maharashtra	0.61	93,50,424	42.10	7.08
Rajasthan	7.01	1,10,53,368	79.18	8.37
Tamil Nadu	3.05	48,09,240	30.93	3.64
Telangana	3.03	47,77,704	46.18	3.62
Uttar Pradesh	8.04	1,26,77,472	62.51	9.60

Note: CUF of 18% is assumed to determine the generation
Source: Total electricity consumption - 2030 – (CEA, 2022)

Considering the Combined Margin emission factors as mentioned previously, Table 13 shows the potential avoided GHG emissions for states with the largest cropland available under the theoretical scenario. The avoided GHG emissions in all cases were found to be higher than India's total gross GHG emission reported in 2020. The estimated generation from the potential installation was found to be much higher than the estimated electricity consumption projected for the respective states in 2030.

Beyond optimizing land productivity, AgriPV can also support emission reduction by replacing fossil fuel-based electricity with carbon-neutral energy. Tables 12 and 13 demonstrate the potential scale of emissions that could be avoided through AgriPV deployment scenarios (Section 2.4). Although the volume of avoided emissions is similar to that of conventional solar PV systems, AgriPV stands out by allowing continued agricultural production, thereby significantly improving overall land-use efficiency.

4.0. EMPLOYMENT GENERATION AND RURAL ECONOMIC BENEFITS

The rapid growth of renewable energy, particularly in solar PV and emerging technologies like AgriPV, is reshaping global employment patterns, creating millions of jobs while requiring targeted policies to enhance workforce capacity, gender inclusion, and skill development for a just energy transition.

The global shift toward renewable energy is transforming employment patterns, with significant implications for economic growth and social equity. Clean energy job creation is outpacing that of the fossil fuel sector, signalling a fundamental change in the global labour market. As per the IEA (2024), the energy sector workforce grew by 3.8% in 2023, reaching 67 million jobs—largely driven by rising investments in clean energy. While employment in fossil fuels remains steady (IEA 2024), its share is gradually declining as countries intensify efforts to transition to low-carbon energy systems. Among emerging technologies, AgriPV systems—combining solar PV installations with agricultural land use— can contribute to clean energy generation and could provide higher employment opportunities compared to other RE technologies. These systems create job opportunities across multiple phases, including construction, operation, maintenance, and eventual decommissioning.

This section explores AgriPV's employment potential by estimating direct, indirect, and induced job creation across its lifecycle. It also compares AgriPV's employment impact with that of other renewable and conventional energy technologies, offering a holistic view of its contribution to sustainable workforce development in the evolving energy landscape.

Employment in the renewable energy sector can be broadly classified into three main categories:

- Direct Employment – Jobs that are directly linked to the planning, construction, installation, and operation of renewable energy projects. In the context of AgriPV, this includes roles in system design, project development, construction, operations and maintenance, as well as agricultural activities managed by farmers under AgriPV systems.
- Indirect Employment – Jobs generated along the supply chain that supports renewable energy deployment. This includes the manufacturing of components such as solar panels, inverters, and mounting structures, as well as logistics, transportation, and financial services connected to renewable energy investments.
- Induced Employment – Jobs created as a result of increased economic activity from direct and indirect employment. These arise from greater household spending in sectors such as retail, housing, education, and healthcare, especially in areas where renewable energy projects are implemented.

Understanding the employment impact of AgriPV across these categories is essential for evaluating its broader socio-economic benefits and potential contributions to a just energy transition.

4.1. Energy employment trends

Global employment in the renewable energy sector continues to rise, reaching 16.2 million jobs in 2023—up from 13.7 million in 2022 (IRENA 2024). Solar PV remains the leading source of employment, contributing 7.1 million jobs or 44% of total renewable energy employment. Other notable contributors include biofuels (2.8 million jobs), hydropower (2.3 million jobs), and wind energy (1.5 million jobs) (IRENA 2024).

In India, the renewable energy workforce has crossed the 1 million mark, within the broader national energy workforce of 8.5 million. Solar PV leads the sector with around 3,19,000 jobs—2,38,000 in grid-connected projects—while the wind sector employs roughly 52,000 people (IRENA 2024). This growth underscores the increasing role of renewables in India's job market as the country scales up its clean energy transition. To meet its target of 500 GW of non-fossil fuel-based capacity by 2030, India is expected to require a substantial increase in workforce capacity. Estimates suggest that achieving this goal could generate over 3.4 million direct jobs in construction, installation, and operations, along with millions more in indirect and induced employment across manufacturing, supply chains, and supporting services. This presents a significant opportunity for skill development and job creation, especially in rural and semi-urban regions.

Gender disparity continues to be a significant challenge in the renewable energy sector, especially within decentralized solar PV. Globally, women make up 40% of the solar PV workforce, but regional representation varies widely. In India, women comprise only 21% of the decentralized solar workforce, compared to 28% in Uganda, 35% in Nigeria, 37% in Ethiopia, and 41% in Kenya—bringing Africa's average to 38% (IRENA, 2024a). Furthermore, women are primarily engaged in administrative and non-technical roles, with limited participation in technical, engineering, and leadership positions. Studies on employment in India's renewable energy sector are often assessed using full-time equivalent (FTE) job-years per megawatt (MW) installed, capturing both direct and some indirect jobs, while excluding induced employment. Job creation varies by technology type and project phase, including business development, design, construction, and operations and maintenance. Rooftop solar projects generate notably higher employment per MW compared to ground-mounted systems. In contrast, wind power and solar PV manufacturing yield relatively fewer jobs. Small-scale hydro and biomass projects also exhibit strong employment intensity, whereas conventional energy sources—such as coal, gas, nuclear, and large hydro—offer comparatively lower employment generation per MW(CEEW 2017, 2019, 2023).

A study in Bangladesh found that AgriPV generates the highest male and female employment among energy sources, creating an estimated 6.64 million jobs for men and 5.57 million for women annually per 10 GW (Kamal et. al., 2024). AgriPV projects alone are expected to generate approximately 5.5 FTE jobs per MW across different stages, including installation, operation, and maintenance(CSTEP 2024). These projections underscore the employment potential of AgriPV and the need for targeted skill development to meet workforce demands in the sector. Greater gender inclusion, particularly in technical and leadership roles, is crucial to ensuring equitable workforce participation in the sector—failure to do so may lead to persistent disparities and missed opportunities.

Table 14 – Full-time equivalent (direct and indirect jobs) for various generating technologies

Technology	FTE Jobs/ Years per MW
AgriPV	~5.5
Rooftop Solar	~ 24.7
Ground Mounted Solar	~ 3.4
Wind Power	~ 1.3
Small Scale Hydro	~ 13.8
Biomass	~ 16.2
Coal (Thermal)	~ 1.6
Gas (Thermal)	~ 1.3
Nuclear	~ 3.7
Large Hydro	~ 2.7

Source: CSTEP 2024,CEEW 2019, CEEW 2017, CEEW 2022

4.2. Employment estimation model

India's demographic trends indicate a significant annual expansion of its workforce. The International Labour Organization's India Employment Report 2024 (ILO 2024) estimates that approximately 13 million individuals will enter the labour force each year, driven by population growth and age distribution. This highlights the urgent need for adequate job creation to absorb the rising number of job seekers.

AgriPV presents a significant opportunity for job creation alongside its energy and environmental benefits. Using an established employment factor of 5.5 full-time equivalent jobs per MW of installed capacity, workforce demand spans business development, construction, installation, operations, and maintenance. As AgriPV deployment scales, it is expected to contribute to rural employment, skill development, and economic growth, highlighting its socio-economic potential within the renewable energy sector.

Table 15 – Total employment generation from each potential AgriPV deployment scenario

Scenario	Theoretical potential scenario	Commercial potential scenario	Commercial potential scenario – feasible crop types	Commercial potential scenario – States + feasible crop types
Potential AgriPV installation (TWp)	65.06	6.43	4.78	3.89
Million FTE/MW for AgriPV	357.83	35.36	26.29	21.40
Estimated average annual employment from each potential AgriPV deployment scenario – 2025 to 2030				
Average annual employment (million FTE)	59.64	5.89	4.38	3.57

Table 15 underscores the employment generation potential for AgriPV systems considering the deployment scenarios from Section 2.4. Under the Commercial potential scenario – States + feasible crop types, AgriPV deployment could generate 21.40 million full-time equivalent (FTE) jobs by 2030, translating to an average annual job creation potential of 3.57 million FTE. Given that 13 million individuals are expected to enter India's labour force each year, this contribution would account for ~27% of the annual workforce addition – assuming each individual works for 1 FTE, highlighting AgriPV's role in supporting employment growth.

The effective integration of AgriPV for local community benefits requires targeted policy interventions that enhance rural employment, strengthen skill development, and drive inclusive economic growth. Policies and training programs should be designed to actively involve women in technical, agricultural, and managerial roles, ensuring a more equitable and inclusive energy transition.

5.0. EVALUATING UPSTREAM ENERGY BENEFITS OF AGRIPV

The integration of distributed solar PV systems like AgriPV enhances grid stability, reduces transmission losses, and optimizes infrastructure investments, but requires strategic grid management and investment in balancing mechanisms to address intermittency and demand fluctuations.

The modern power system is undergoing a fundamental shift from a centralized generation model to a more decentralized framework driven by distributed energy resources (DERs) such as AgriPV. Government policies promoting local renewable energy generation, coupled with environmental concerns and the need to reduce dependence on fossil fuels, have accelerated the adoption of distributed power generation, particularly solar PV systems.

The integration of distributed solar PV systems in modern power networks poses both technical challenges and strategic opportunities for power utilities. As installations grow, networks may need upgrades to manage bidirectional power flow and ensure smooth operation. Generation and consumption fluctuations create supply-demand imbalances, affecting power quality through voltage and frequency deviations. While these upgrades involve costs, AgriPV integration can provide significant yet often underestimated benefits to distribution companies (DISCOMs). Additionally, it aids DISCOMs in meeting their Renewable Purchase Obligations (RPOs) and lowers overall transmission and distribution (T&D) losses by enabling localized energy generation closer to the point of consumption. The integration of distributed solar, such as AgriPV may reduce the need for additional generation, transmission, and distribution capacity, leading to cost savings and grid efficiency(Auroville Consulting 2023).

By enhancing grid resilience and efficiency, distributed solar help optimize infrastructure investments. However, effective grid management, including smart technologies and energy storage, is crucial to address intermittency and demand fluctuations. These advantages translate into financial savings by optimizing capital expenditure and deferring investments required to expand network infrastructure in response to growing energy demands. Thus, with appropriate grid management strategies, the widespread adoption of solar PV systems can support a more efficient, cost-effective, and resilient power distribution network.

This section categorizes the benefits of solar energy generation from AgriPV systems compared to a coal-based thermal power plant during the generation phase. The analysis focuses on energy benefits and emissions reduction.

5.1. Evaluate the value of distributed solar and storage

To assess and quantify the energy benefits of integrating AgriPV into the modern power network, this study employs the Value of Distributed Energy Resource (VoDER) methodology – detailed in Annexure. Table 16 provides the details of the Energy Benefits and Avoided Emission Benefits from the tool. This approach has been implemented in an online web tool, Solva, designed to evaluate the value of distributed solar and storage. The tool performs a simplified power flow analysis, considering the integration of Distributed Energy Resources (DERs), and provides insights into active power distribution and voltage profiles within the network (Auroville Consulting 2023a). The outputs of the tool include both energy benefits and avoided emission benefits, offering a comprehensive evaluation of DER integration.

Table 16 – Network and avoided emission benefits

Benefits		Unit	Description
Energy Benefits	Avoided cost of energy (ACE)	INR/kWh	ACE reflects savings in generation, transmission, distribution, and operational expenses by offsetting demand with local renewable energy
	Avoided distribution capacity cost (ADCC)		ADCC is the deferred investment in distribution capacity due to DERs reducing grid congestion and peak demand
	Avoided transmission capacity cost (ATCC)		ATCC is the avoided investment in contracting transmission capacity due to offsetting demand with local distributed energy resource
	Avoided generation capacity cost (AGCC)		AGCC is the avoided investment in contracting generation capacity due to offsetting demand with local distributed energy resource
Avoided Emission Benefits	Avoided CO2 emission costs	INR/kWh	The external costs of fossil fuel combustion are reflected in the avoided costs associated with mitigating pollution-related economic and environmental impacts due to offsetting demand with local distributed energy resource
	Avoided SO2 emission costs		
	Avoided NO2 emission costs		
	Avoided PM2.5 emission cost		

Source: Auroville Consulting 2023a

5.2. Case study – HT Feeder Erode district, Tamil Nadu

Case studies are essential for evaluating real-world energy systems, offering insights into their technical, economic, and environmental impacts. They help address challenges, enhance system performance, and guide policy development. In the context of AgriPV, studying its integration with the power network is crucial for assessing its effects on distribution infrastructure, grid stability, and energy management. These evaluations highlight key benefits such as better voltage regulation, lower transmission losses, and increased local energy security, supporting the shift toward decentralized renewable energy systems.

To analyse the upstream benefits of integrating an AgriPV system into the power network, a sample feeder was selected for evaluation. The feeder, part of the Erode substation in Tamil Nadu, operates at 22 kV with a maximum power-carrying capacity of 10 MW. It spans 9.78 km and supports a sanctioned load of 27.87 MW. A total of 17 distribution transformers (DTs) are connected to this feeder, supplying electricity to 5,036 consumers, 77% of whom belong to the domestic category. The feeder records an annual energy consumption of 8,466.03 MUs, with a distribution loss of only 0.60%. Despite managing a load that is approximately 50% of the feeder's thermal capacity, it has demonstrated stable voltage performance with no violations during the sample year.

The Tamil Nadu (TN) state net load profile for the year 2023 was considered for the analysis. In 2023, the state added 1,362 MW of RE (solar and wind), which was entered as the state's RE capacity addition in the tool (TN, 2023; TN, 2022). The marginal cost to be replaced was taken from the IEX data for the year 2023 (IEX, 2023) and the transmission loss considered was 6% (TN, 2023).

Geographic Information System (GIS) data was used to identify suitable land for AgriPV installations within the Erode district, applying technical and commercial constraints to ensure feasibility. A 2.00 MW AgriPV system was selected for integration into the solar HT feeder. The point of interconnection was varied between the sending end, close to the substation, and at the middle end, approximately at the middle of the HT feeder, to identify a suitable location. The system size was determined based on the maximum allowable size under PM-KUSUM component A – 2.00MW. Additionally, a distance of 5,000m from the electrical substation was another criterion of selection.

5.2.1. Results

The integration of the distributed solar – in this case, assumed to be an AgriPV system – was interconnected at the middle end of the power network. A HT feeder-level analysis was carried out to study the impact of integration on the power network.

Figure 7 – Visual representation of BAU case (marked in grey) with no DER integrated in the power network, showcasing the voltage violation and distribution loss in the BAU case.

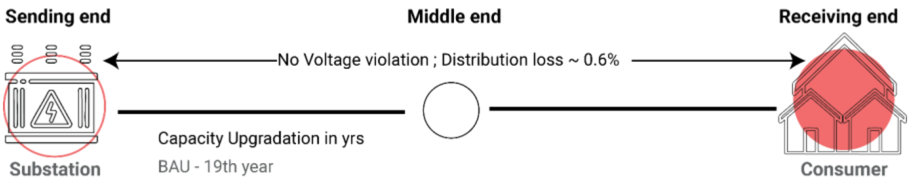
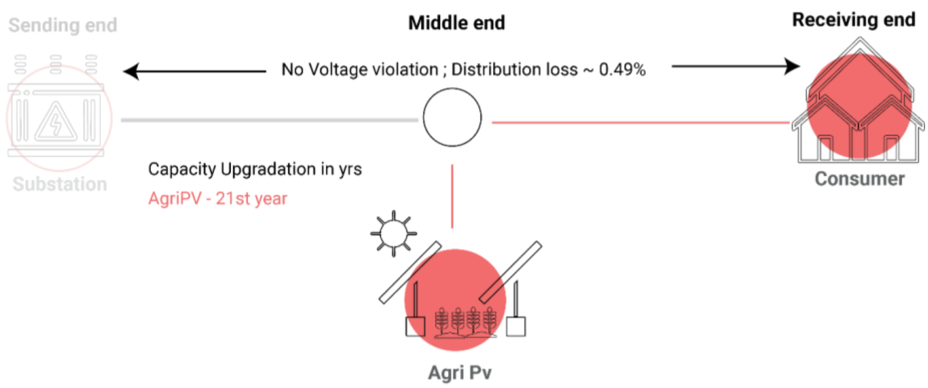
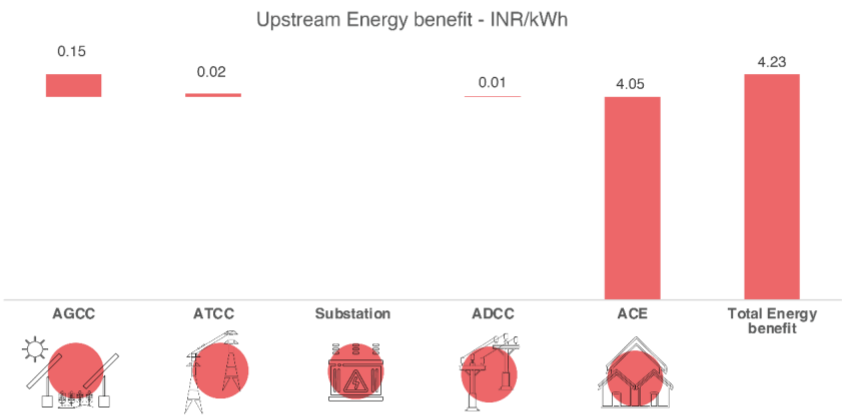


Figure 8 – Visual representation of AgriPV case where it is interconnected at the middle end of the power network, showcasing no impact on voltage violations and reduced distribution loss in AgriPV case.



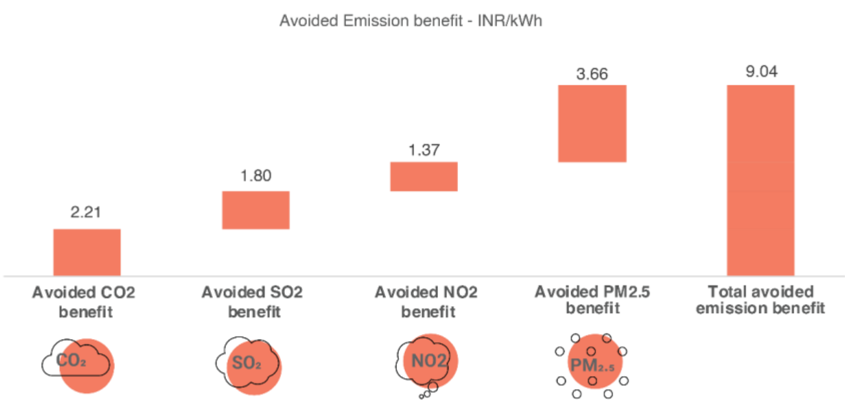
Integration of 2.00MW of DER at the middle end of the power network resulted in no further violation of the voltage parameters while facilitating a slight reduction in the distribution loss, owing to interconnection made closer to the point of consumption. There was no change observed in peak handled by the feeder for the first year, indicating that the peak loads are beyond the solar hours and integration of DER did not contribute to reduction in these peak loads. However, integration of DER does contribute to deferment of the capacity upgradation by 2 years – upgradation in business-as-usual (BAU) case – 19th year, while upgradation after integration of DER, was suggested in 21st year of the analysis.

Figure 9 – The upstream energy benefits for 2MW AgriPV interconnected at the middle end in INR/kWh



A 2MW AgriPV system would annually generate 2.85 MU assuming a CUF of 18% and 330 sunny days. This would result in a total energy benefit of approximately INR 1.2 crore per year along with a total avoided emission benefit of approximately INR 2.57 crore per year as shown in figure 10 below.

Figure 10 – The avoided emission benefits for 2MW AgriPV interconnected at the middle end in INR/kWh



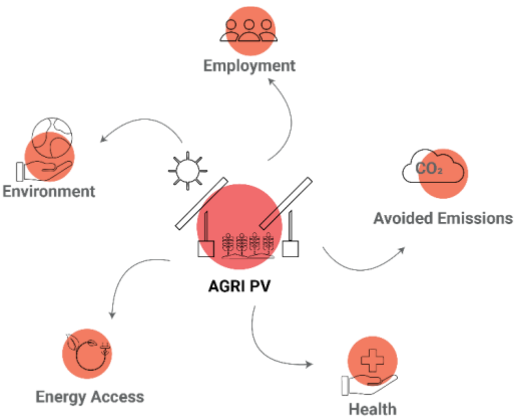
The above analysis highlights the advantages of integrating an AgriPV system into the power network, not only quantifying these benefits in monetary terms but also demonstrating improvements in power infrastructure maintenance and the added societal value of reducing reliance on fossil fuel-based electricity generation.

6.0. Co-benefits of AgriPV integration

AgriPV has the potential to democratize energy access, enhance rural socio-economic resilience, and integrate decentralized solar power with agriculture, but its widespread adoption depends on financial accessibility, policy support, and farmer participation.

The transition to renewable energy must extend beyond technological advancements to encompass socio-economic transformations that prioritize inclusivity and equitable access. AgriPV presents an opportunity to integrate decentralized solar energy with agriculture, addressing challenges related to energy and food security. However, ensuring AgriPV fosters increase in employment, contributes to emission reduction while improving health and energy access for the local communities is key to maximizing its impact. This section evaluates the co-benefits of integrating AgriPV systems.

Figure 11 – Visual representation of co-benefits of AgriPV integration



6.1. Employment

The employment generation potential of AgriPV systems has been detailed in section 4.0 of this report. To enable the integration of AgriPV systems, the creation of new job roles—such as AgriPV advisors, structural engineers, and equipment operators—will be essential (CSTEP, 2024). These roles will require specialized skills related to the installation and maintenance of AgriPV infrastructure. To ensure that local communities can access these opportunities, targeted skill development and training programs should be designed and implemented, with a focus on long-term benefit.

It is estimated that around 3.57 million FTEs would be needed if AgriPV systems were deployed for select crop types across states with the largest areas of commercially available cropland (Section 4.2). This represents approximately 27% of the projected 13 million new entrants to the job market. While this estimate is idealistic, it provides a valuable perspective on the significant employment potential associated with integrating AgriPV into the energy sector.

6.2. Avoided Emissions

The avoided emission from integration of AgriPV is detailed in section 3.0 of this report. The integration of AgriPV systems into the power sector is based on the assumption that older fossil-fuel-based thermal power plants—particularly coal-fired plants—would be replaced. To assess the potential for emission reductions, the scenarios outlined in section 2.4 are used, alongside an operating margin of 0.757 $kgCO_2/kWh$.

Under a scenario where AgriPV is deployed for selected crop types across states with the largest commercially available cropland, it is estimated that up to 4.64 $GtCO_2$ per year in emissions could be avoided. This estimate is approximately 1.5 times greater than India's total reported GHG emissions in 2020. While these projections are idealized, they provide a compelling indication of AgriPV's potential to significantly reduce emissions from electricity generation.

Beyond environmental benefits, the integration of AgriPV also presents substantial economic advantages, as detailed in Section 5.2.1. The replacement of fossil-fuel-based power generation with renewable alternatives like AgriPV not only curbs emissions but also delivers multiple layers of value, including long-term cost savings.

6.3. Human Health

Coal-fired power plants are a major source of air pollution in India, with severe consequences for public health. These power plants release vast amounts of sulphur dioxide, nitrogen oxides, and particulate matter (PM), which contribute significantly to the formation of fine particulate matter ($PM_{2.5}$) in the atmosphere. Exposure to elevated levels of $PM_{2.5}$ is directly linked to respiratory and cardiovascular diseases, making coal-based energy generation one of the most harmful contributors to India's pollution crisis.

According to the International Energy Agency's Clean Coal Centre (IEACCC), coal-fired thermal power stations without adequate pollution control technologies account for over 50% of human-made SO_2 emissions, 30% of NO_2 emissions, and about 20% of PM emissions in India, exacerbating the country's already alarming air pollution levels (IEACCC, 2008). The health consequences are staggering—research published in the Proceedings of the National Academy of Sciences (PNAS) estimates that emissions from existing and planned coal-fired power plants contribute to approximately 1,12,000 premature deaths every year in India. If the proposed plants were not built, at least 8,44,000 premature deaths could be prevented over their operational lifetimes. These numbers highlight the urgent need for India to transition away from coal-based energy and implement stronger pollution control measures to protect public health.

6.4. Energy Access and Energy Independence

Access to electricity is defined by key attributes such as availability, reliability, quality, and affordability (Jain et al., 2016). AgriPV systems hold strong potential to improve energy access and enhance energy independence for rural communities by enabling decentralized electricity generation directly at the point of use. When integrated with energy storage systems, AgriPV can help address power shortages during solar hours and provide a more stable supply, especially in regions with unreliable grid connectivity. For farmers, AgriPV can reduce dependence on diesel for irrigation, lower energy costs, and ensure more reliable electricity for agricultural operations. It also offers the opportunity to sell surplus electricity, which can further strengthen local energy autonomy. Beyond individual farms, AgriPV can play a transformative role in rural electrification by extending access to clean and affordable energy to entire communities—powering homes, schools, health centres, and small businesses.

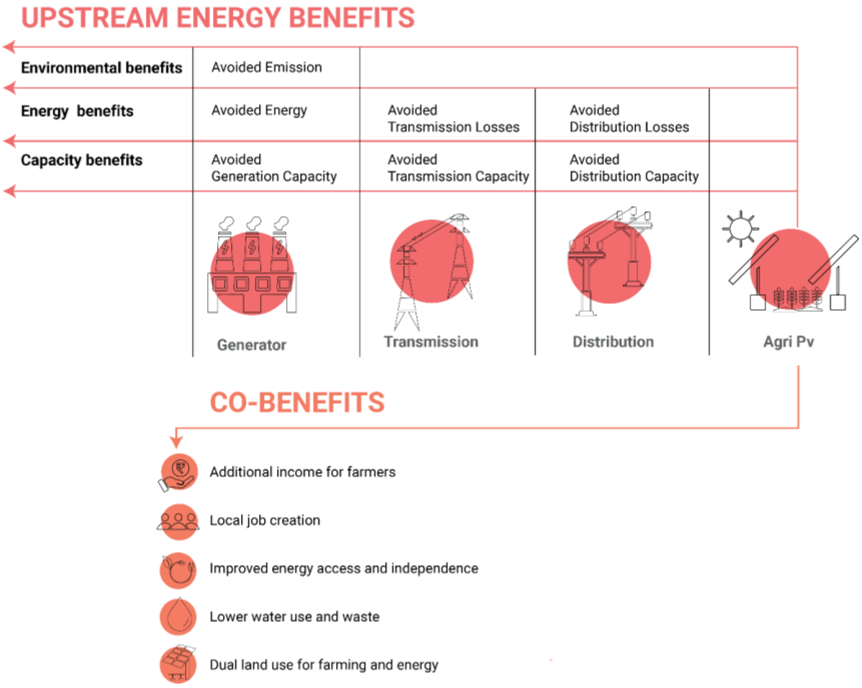
6.5. Environment

Effective resource management is central to evaluating the environmental sustainability of electricity generation methods. While emissions are a key metric, the broader ecological impact also depends on factors such as water consumption, land use, soil health, and waste generation. In comparison to coal-based thermal power plants, AgriPV systems demonstrate significant environmental advantages by reducing pressure on these critical natural resources.

Coal-fired power plants are extremely water-intensive, relying on large volumes for cooling, steam generation, and pollution control. These plants typically consume between 2 to 3.5 cubic meters of water per MWh of electricity produced—placing immense stress on freshwater resources, especially in water-scarce regions. AgriPV systems, on the other hand, use only a fraction of this water—mainly for occasional panel cleaning—requiring just 0.02 to 0.1 cubic meters per MWh (GIZ, 2025). Thermal power plants not only occupy large areas but also contribute to further land degradation through coal mining and ash disposal. AgriPV systems, in contrast, promote dual land use, requiring just 3 to 5 hectares per MW while allowing continued agricultural activity beneath or around solar installations.

Coal plants also generate significant waste—most notably fly ash, with a 500 MW facility producing up to 250-300 tons annually. Soil contamination is a major concern with coal-based power generation, with Spheroidal carbonaceous particle (SCP) concentration of above 500g/dry matter found at sites close to coal plants (Luo et. al., 2024). These pollutants degrade soil quality, compromise agricultural productivity, and pose risks to groundwater. In contrast, AgriPV systems generate minimal operational waste. While panel end-of-life disposal is a concern, advances in recycling technologies are improving material recovery rates, making solar a far less waste-intensive energy option.

Figure 12 – Summary of the upstream energy benefit and co-benefits of integrating AgriPV in the power network



7.0. GAPS IN POLICY AND REGULATORY FRAMEWORKS

With 86% of farms held by marginal and smallholders, they are central to AgriPV adoption. Despite its potential for energy security and sustainable farming, uptake is limited by financial and regulatory gaps. Policies must prioritize income diversification, energy access, and social acceptance.

Currently, AgriPV falls under multiple policies governing solar energy, agriculture, land use, and electricity distribution, none of which are specifically designed for AgriPV implementation. This misalignment creates regulatory uncertainties and barriers to adoption. This section analyses India's power sector policies and regulatory frameworks that are relevant to AgriPV installation, identifying key gaps and opportunities. Addressing these challenges through targeted policy reforms can foster a supportive environment, accelerating AgriPV deployment and contributing to the renewable energy transition of electricity generation.

Approximately 86% of agricultural landholdings in India are classified as marginal (<1 hectare; ~69%) and small (1–2 hectares; ~18%) (Kareemulla et al., 2021; Sharma & Malik, 2021), highlighting the highly fragmented nature of land ownership. To enable effective integration of AgriPV, the policy and regulatory framework must specifically address the needs of small and marginal farmers and create provisions that support their participation and uptake.

The most relevant initiative supporting decentralized solar adoption in agriculture is the PM-KUSUM scheme, launched in 2019. It comprises three components: Component A promotes the installation of 10 GW of decentralized solar plants (up to 2 MW each) on barren or cultivable land, including elevated structures that permit continued farming underneath. These projects, developed by farmers, co-operatives, or FPOs, sell electricity to local DISCOMs at pre-fixed feed-in tariffs, with procurement-based incentives provided by the Ministry of New and Renewable Energy (MNRE). Component B aims to solarize 20 lakh standalone agricultural pumps, replacing diesel-based irrigation, while Component C focuses on solarizing 15 lakh grid-connected pumps to reduce agricultural electricity subsidies.

The broader policy and legal foundation for renewable energy integration is provided by the Electricity Act (2003) and the National Tariff Policy (2016). The Electricity Act, mandates State Electricity Regulatory Commissions (SERCs) to set renewable energy procurement targets, while the National Tariff Policy strengthens Renewable Purchase Obligations (RPOs) for DISCOMs, encouraging greater uptake of renewable energy (MoP, 2016).

The integration of solar energy systems into the power network is also shaped by regulations governing the interconnection of distributed solar energy systems. The Central Electricity Authority and State Electricity Regulatory Commissions have issued technical standards and interconnection guidelines to ensure the safe and reliable integration of distributed energy resources (CEA, 2013).

Land-use regulation adds another layer of complexity, as it falls under the Concurrent List and is governed at the state level. Most state land revenue codes and land reform laws restrict non-agricultural activities on farmland, requiring formal land-use conversion before solar installations can proceed.

7.1. Policy Gaps & Recommendations

As highlighted earlier, marginal and small landholding farmers constitute the majority of agricultural landholders in India. To fully realise the energy and co-benefits of integrating AgriPV into the power system, it is essential to position these farmers as key beneficiaries. In this context, the existing policy and regulatory landscape has been examined to identify critical gaps and propose recommendations that can enable and accelerate AgriPV adoption among marginal and small landholding farmers.

The identified gaps are organized into key thematic categories—legal & institutional recognition, land-use, financial, environmental, and grid interconnection. While not exhaustive, these gaps represent critical entry points or "low-hanging fruit" that, if addressed, can inform targeted policy and regulatory interventions to facilitate the adoption of AgriPV systems, particularly among marginal and small landholding farmers.

Table 17 – Summary of the identified gaps and recommendations to facilitate AgriPV systems in the existing policy and regulatory framework

Category	Identified gaps	Recommendations
Legal & Institutional recognition	• Lack of definition	• Introduce a definition of AgriPV systems in policy framework
Land-use barriers	• Land reclassification required for non-agricultural activity – such as electricity generation • Land leasing restrictions on agricultural land	• Encourage dual land use with exemptions for solar energy generation • Flexible land leasing regulation could increase investments from third parties.
Financial	• Absence of subsidies for AgriPV • Difficulty in accessing credit lines • Financially unfeasible due to low feed-in tariff	• Introduce capital subsidy for AgriPV to reduce strain of initial investment for farmers • Facilitate ease-of-access for credit lines for farmers • Set location and size specific feed-in tariff
Environmental	• Absence of requirement for environmental impact assessment for AgriPV	• Introduce compulsory environmental assessment for AgiPV to ensure low impact on surrounding biodiversity and ecosystem
Grid Interconnection	• Requirement of minimum size of installation for interconnection • Tedious interconnection regulations and procedures involving high cost for upgradation of infrastructure	• Relaxation on the minium size for installation under AgriPV – facilitating marginal and small landholding farmers • Relaxation of interconnection requirements such as – distance from substation. Financial support for farmers in case upgradation of infrastructure is required.

7.1.1. Legal & Institutional recognition

AgriPV currently lacks a formally accepted definition, leading to ambiguity across policies, regulations, and implementation frameworks, which in turn hinders its widespread adoption. Institutional recognition is crucial to formalize AgriPV as a distinct and credible renewable energy pathway, that integrates agriculture and solar generation. This includes defining AgriPV in legal and policy documents, integrating it within RPOs and developing compliance mechanisms.

Strengthening legal and institutional frameworks will enable more coordinated action across central and state agencies, improve access to incentives, and foster investor and farmer confidence in AgriPV deployment.

7.1.2. Land-Use barriers

The deployment of AgriPV in India faces several land-use related regulatory and policy challenges. Existing land-use classification laws often restrict dual-use of land. Agricultural land must typically be reclassified as non-agricultural if it is used for activities like electricity generation, potentially disqualifying farmers from crucial agricultural subsidies. Since subsidies constitute a major component of farmers' financial support, the risk of losing them serves as a strong deterrent to adopting AgriPV.

Additionally, state-specific regulations often restrict leasing of agricultural land for non-agricultural purposes, making it difficult for third parties or developers to partner with farmers for AgriPV projects. Additionally, land ceiling laws in several states impose limits on maximum landholding, which can constrain the development of financially viable AgriPV systems—particularly because larger installations are more cost-effective due to economies of scale.

Addressing these land-use barriers through policy reforms that enable dual-use classification, flexible leasing norms, and tailored guidelines for AgriPV can significantly enhance its adoption, especially among small and marginal farmers.

7.1.3. Financial

Financial accessibility remains a key barrier to AgriPV adoption, particularly for small and marginal farmers. The high upfront investment required for system installation is often unaffordable without external support. Existing capital subsidy schemes, such as those under PM-KUSUM, are limited in scope and primarily target standalone systems, leaving AgriPV-specific needs unaddressed.

Access to credit continues to be limited. Although India has amended its priority sector lending norms to include renewable energy projects in agriculture—enhancing financing opportunities—significant hurdles remain, especially for small-scale borrowers and those relying on NBFCs. As a result, despite supportive policies, financing for renewable energy infrastructure in agriculture remains inconsistent and only partially accessible.

Even when systems are installed, low feed-in tariff rates under current schemes compromise the financial viability of AgriPV, limiting its potential to generate meaningful returns for farmers. Addressing these issues will require targeted financial instruments, improved subsidy frameworks, and tailored credit mechanisms.

7.1.4. Environmental

There is broad agreement among experts and researchers that the environmental impacts of solar PV systems—particularly AgriPV—are not yet fully understood. While the role of solar energy as a clean and cost-effective power source is well recognized, its potential effects on critical ecosystem services and biodiversity require closer examination. Addressing these concerns is essential to ensure that the transition to renewable energy is both sustainable and ecologically responsible.

A key gap identified in the study is the lack of mandatory Environmental and Social Impact Assessments (ESIA) for AgriPV installations. In India, solar projects are currently categorized under the "white category" by the Ministry of Environment, Forests, and Climate Change (MoEFCC), exempting them from the requirement for environmental clearance. This regulatory gap poses risks to ecosystems—especially in areas rich in biodiversity—as AgriPV systems may affect soil health, water resources, and local habitats. Moreover, environmental impacts can vary significantly depending on the scale of AgriPV installations, with smaller systems generally posing lower risks. This underscores the importance of careful site selection and the development of robust land-use planning guidelines.

AgriPV systems should be subject to a dedicated ESIA process that accounts for their ecological impact. Clear regulations on site selection and system scale are needed to protect biodiversity and support sustainable deployment.

7.1.5. Grid Interconnection

AgriPV deployment under PM-KUSUM Component A faces significant entry barriers, including a minimum system size of 500 kW—equivalent to about 1.6 hectares (assuming an AgriPV density of 0.3MW per hectare—excluding marginal and many small landholding farmers from eligibility. While the Green Open Access policy offers a lower threshold of 100 kW, its implementation remains limited due to lack of enabling regulations in many states and UTs.

Additionally, interconnection criteria under PM-KUSUM component A—such as the 5 km distance cap from substations—and the burden of covering evacuation infrastructure costs make adoption financially unviable for many marginal and small landholding farmers. The requirement for technical know-how and complex regulatory procedures further discourages participation among farmers.

Lowering the minimum capacity or enabling group-based business models can help include smallholders under PM-KUSUM. Fast-tracking of Green Open Access implementation and offering financial support for interconnection costs and technical assistance can further aid in adoption of AgriPV among farmers.

7.1.6. Conclusion

AgriPV presents a transformative opportunity to diversify farmer incomes, democratize energy access, and promote climate-resilient agriculture—particularly for India's marginal and small landholders who constitute the majority of the farming population. However, its widespread adoption is limited by a combination of legal, financial, regulatory, environmental, and social barriers. The absence of a dedicated definition, policy and regulatory framework and limited institutional recognition has created ambiguity in implementation. . However, realizing AgriPV's full potential requires addressing a set of interconnected challenges.

Land-use restrictions—such as land reclassification, leasing limitations, and land ceiling regulations—further constrain deployment. Streamlining land-use approvals, enabling lease-based models, and allowing dual-use of agricultural land under state-specific reforms will be critical. On the financial front, high capital costs, limited access to institutional credit, and lack of tailored support mechanisms disproportionately affect smallholders. Addressing this requires targeted financing instruments like capital subsidies, group-based business models via FPOs or cooperatives, and enabling easier access to credit through NBFCs and cooperatives.

Environmental concerns also remain insufficiently addressed, particularly due to the exemption of Environmental and Social Impact Assessments (ESIAs) for solar farms. Introducing scalable ESIA guidelines based on project size and sensitivity of location, alongside land-use and biodiversity safeguards, will be essential for responsible deployment. Grid interconnection challenges—such as minimum installation size, substation distance limits, high infrastructure costs, and complex technical approvals—also deter participation. These can be mitigated by reducing minimum system size requirements, expanding Green Open Access, subsidizing infrastructure, and providing technical support to farmers.

Lastly, social acceptance remains a critical factor. Many farmers lack awareness, technical knowledge, and confidence in the viability of AgriPV. Building trust through awareness campaigns, demonstration projects, training initiatives, and showcasing successful AgriPV business models will be key to driving adoption.

In conclusion, bridging these gaps through coordinated legal, financial, environmental, and infrastructural reforms—coupled with active farmer engagement—will be essential to unlock AgriPV’s full potential as an inclusive and community-driven clean energy solution.

8.0. RECOMMENDATIONS

The report highlights the significant potential of AgriPV (Agrivoltaics) as a solution to India's growing energy and agricultural challenges. AgriPV enables dual land use, allowing for solar power generation alongside agricultural activities, thereby increasing land use efficiency and promoting sustainable development. The findings indicate that AgriPV can contribute substantially to India's renewable energy targets, food security, and water conservation efforts. To scale AgriPV in India, the short-term focus should be on clarifying land-use policies, launching pilot projects for energy sharing, and offering financial support to small landholding farmers. In the medium term, cooperative models, peer-to-peer energy trading, and inclusive grid access must be promoted, along with environmental safeguards. Long-term efforts should institutionalize AgriPV within national renewable and rural development plans, establishing large-scale clusters to maximize land use and drive rural economic growth.

8.1. Key findings:

- Potential: The estimated AgriPV potential in India is over 3,890 GW, leveraging approximately ~6% of existing agricultural land for dual-purpose use.
- Generation: The potential power generation from AgriPV could contribute significantly to India's renewable energy mix, with projections suggesting annual electricity output of over 5,600 TWh if fully utilized.
- Demand Alignment: This generation capacity exceeds India's expected electricity demand in 2030, projected to be around 2,500 TWh, showcasing AgriPV's role in meeting future energy needs.
- Water Savings: AgriPV systems also offer up to 90% water savings compared to fossil-fuel-based thermal power plants during the generation phase.
- Irrigation: AgriPV systems additionally contribute to water savings for irrigation by reducing evapotranspiration from crops, thanks to partial shading from solar panels.
- Infrastructure: Upstream energy benefits of integrating AgriPV facilitate deferral in infrastructure costs and support emission reduction.
- Co-benefits: Co-benefits of AgriPV include employment generation in solar manufacturing, installation and maintenance, health improvements from reduced emissions, expanded energy access, environmental protection, decreased dependency on fossil fuel imports, and improved grid stability.
- Challenges: Despite its significant potential, AgriPV faces major hurdles including high upfront costs, unclear policies, complex grid interconnection processes, restrictive land-use regulations, and limited farmer awareness. Overcoming these challenges is essential to fully unlock its benefits at scale.

8.2. Recommendations:

To accelerate the adoption and effectiveness of AgriPV in India, the following recommendations are proposed:

- Policy and Regulatory Support: Introduction of a clear AgriPV policy with targeted subsidies, tax incentives, and streamlined land-use and interconnection regulations to accelerate deployment.
- Financial support and collaborative Business Models: Support small and marginal farmers through financial aid for interconnection infrastructure, FPO-led models, and public-private partnerships to lower AgriPV's upfront costs.
- Technological Innovation: Research and development efforts should focus on lowering costs, improving crop compatibility, and integrating smart energy management systems into AgriPV setups.
- Farmer Training and Awareness: Education campaigns and capacity-building initiatives should be implemented to enhance marginal and small landholding farmer participation in AgriPV projects.
- Social Acceptance and Energy Democratisation: Support mechanisms that promote energy democratisation for farmers should emphasize benefits like improved energy access, independence, and employment generation to enhance social acceptance.
- Financial Incentives and Income Diversification: Ensuring financial viability through region- and size-specific feed-in tariffs is essential to enable farmers to diversify their income sources.
- Mandatory environmental assessments: Environmental assessments and clearances should be enforced to minimize impacts on biodiversity and ecosystem services, along with continuous monitoring of AgriPV systems to ensure sustainable performance.

Implementing these recommendations is crucial to realise AgriPV's transformative potential for India's marginal and small landholding farmers, enabling them to benefit from clean energy access, diversified incomes, and improved agricultural resilience. A targeted, inclusive approach will ensure that AgriPV becomes not only a tool for sustainable development but also a pathway to equitable rural empowerment and energy democracy.

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10.0. ANNEXURE

10.1. Methodology for evaluating Upstream benefits – Solva Tool

Solva is an open-source python-based toolbox for simulating and analysing the technical and economic benefits of modern power systems with distributed renewable energy (DER) sources. The Solva web tool allows users to:

- Undertake a DT/HT Feeder/Substation level power flow analysis.
- Evaluate the network benefits and social benefits for distributed solar and energy storage.
- Identify system sizes and dispatch strategies to optimize the value of distributed solar and energy storage.

Solva tool helps to accelerate integration of distributed solar energy and storage systems interconnected at the distribution network and support electricity utilities in identifying opportunities for interconnection of distributed solar and energy storage systems (Auroville Consulting 2023a)

The value of distributed energy resource or VoDER methodology takes a systems approach to establishing the value of the electricity generated by DER. DER generation has some unique features: power generation occurs close to the point of consumption, no marginal cost of generation (no fuel cost) and significant environmental advantages over conventional generation based on coal. These characteristics allow the utilities to reduce their energy costs, and avoid generation, transmission and distribution capacity costs. In addition, there are avoided social and environmental externalities of fossil fuel-based generation. Adapting a VoDER methodology represents an opportunity for states and utilities across the country to begin to assess the benefits of distributed generation and better plan for energy investments that provide maximum network and societal benefits. The VoDER methodology can be made a part of:

- Integrated resource planning of utilities
- Determination of feed-in tariffs for distributed solar
- Demand response and demand side management

10.1.1. Energy benefits

This section further explores the concept of energy benefits in terms of avoided costs associated with the integration of AgriPV into the power system. By facilitating local generation and consumption, AgriPV can reduce reliance on centralised electricity supply, leading to significant cost savings across multiple components of the power network.

Avoided Cost of Energy (ACE)

The Avoided Cost of Energy (ACE) represents the reduction in expenses associated with procuring electricity from conventional generation sources. The integration of DERs enables localized power generation, decreasing dependency on electricity from grid which is primarily sourced via fossil fuel-based plants and reducing fuel costs, line losses, and operational expenses. As a result, utilities can optimize energy procurement while enhancing overall network performance.

Avoided Distribution Capacity Cost (ADCC)

The Avoided Distribution Capacity Cost (ADCC) is realized through the reduction in stress on local distribution infrastructure. The proximity of DERs to end-users minimizes strain on transformers and feeder lines, reducing the need for costly network reinforcements. Consequently, utilities can defer or avoid investments in distribution upgrades.

Avoided Transmission Capacity Cost (ATCC

The Avoided Transmission Capacity Cost (ATCC) arises from the reduced need for long-distance electricity transmission. DER integration alleviates transmission network congestion by decreasing peak demand, thereby deferring or eliminating investments in new transmission infrastructure. This not only reduces capital investment in high-voltage transmission infrastructure but also enhances grid reliability and resilience.

Avoided Generation Capacity Cost (AGCC)

The Avoided Generation Capacity Cost (AGCC) refers to the deferred or reduced investment in new power generation capacity due to integration of AgriPV close to point of consumption. By mitigating peak demand and enhancing grid flexibility, DERs (AgriPV in this case) can reduce the need for additional large-scale power plants and associated reserve capacity. This translates to lower capital expenditures and operational costs for utilities, improving the financial viability of the power sector.

Overall, the integration of AgriPV can contribute to substantial cost savings in energy procurement, distribution and transmission infrastructure investments and generation capacity expansion. These avoided costs highlight the economic benefits of integrating AgriPV in the power network, reinforcing the need for supportive policies and strategic investments to maximize their potential.

10.1.2. Avoided emission benefits

The economic and environmental impacts of fossil fuel combustion have become a critical area of research. Emissions from burning coal, oil, and natural gas—such as CO_2, PM10, PM2.5, sulfur oxides (SO_x), and nitrogen oxides (NO_x)—contribute to climate change, respiratory diseases, and environmental degradation, imposing significant costs on public health and infrastructure. Quantifying these externalities, including the social cost of carbon (SCC) and health-related burdens, helps policymakers assess the true cost of fossil fuel-based energy (Auroville Consulting 2023b).

This section examines these economic implications and highlights how DERs can mitigate pollution-related costs, supporting a sustainable energy transition. Research indicates that sustained exposure to an additional 10 µg/m³ of PM10 in ambient air can reduce life expectancy by approximately 0.64 years (EPIC, 2018). By correlating this reduction with a nation's Gross Domestic Product (GDP) per capita, the economic burden of particulate matter pollution can be estimated, providing insight into its external costs to society. In addition, the SCC measures the long-term economic damages associated with each additional tonne of CO_2 emissions. Unlike particulate matter, which has localized health and environmental costs, SCC encompasses broader climate-related impacts, including disruptions to agriculture, human health, and infrastructure. Assigning a monetary value to these externalities is essential for formulating environmental regulations and policy mechanisms that internalize these costs (Auroville Consulting 2023b).

The integration of DERs — such as AgriPV — could be instrumental in reducing these environmental and economic externalities. By decreasing dependence on fossil fuel-based power generation, DERs help mitigate emissions of PM10, PM2.5, CO_2, sulfur oxides (SO_x), and nitrogen oxides (NO_x), leading to improved public health and economic benefits.

The environmental value of Distributed Energy Resources (DERs) is determined by the volume of emissions they help avoid, highlighting their contribution to a sustainable and cost-effective energy transition. This value is further used to quantify the avoided costs of pollutants, based on the emissions rate from a coal-based thermal power plant.

Table 18 – Emission rates for different pollutants

Pollutants	Emission rate (kg/MWh)
CO_2	980.00
SO_2	7.05
NO_2	4.30
PM2.5	1.15

Source: Auroville Consulting 2023a

10.1.2. Case study description

In this analysis, we have considered Tamil Nadu's 2023 net state load profile (solar plus wind) alongside a state-wide distributed energy capacity addition of 887.50 MW for the year 2022–23 (TN, 2023). It is important to note that using the gross hourly load profile instead of the net load would result in an overestimation of Avoided Transmission Capacity Costs (ATCC) and Avoided Generation Capacity Costs (AGCC). The marginal cost of the displaced generator has been taken from IEX 2023 data. A transmission loss of 6% was factored into the simulation.

The system considered is a 2 MW solar installation connected at the mid-point of the distribution feeder. This configuration complies with PM-KUSUM Component A guidelines, which permit a maximum system size of 2 MW and a connection distance of less than 5,000 meters from the substation. With the total feeder length being 9.78 km, the mid-point is approximately halfway along the feeder, thereby meeting the eligibility criteria.

For the conductor, a Racoon-type conductor is assumed, with the following specifications:

- Resistance: 0.371 ohms/km
- Reactance: 0.241 ohms/km
- Peak current carrying capacity: 300 amperes

The analysis timeframe is 25 years, with the feeder's capacity utilization capped at 90%. If this threshold is exceeded more than five times in a year, infrastructure upgradation is recommended. It is assumed that any newly added infrastructure would handle 50% of the load. Additionally, an annual load growth of 5% is assumed for the simulation.

10.2. AgriPV potential calculations

The determination of the GIS potential is described in Section 2.0. However, in this section a brief detail of the crop types and their share considered for the analysis is further detailed. The potential cropland for theoretical, technical and commercial was attained using the GIS information. Further to be able to estimate the total potential of AgriPV, crop-types were considered to allocate appropriate densities of AgriPV on the potential available land. Please find below the percentage share of each crop-type in each state as well as the crop-types distributed among all the states and UT's.

Table 19 – Details the share of each crop-type in each state and distribution of each crop-types in all states and UT's

States	Cereals	Pulses	Sugar	Condiments and Spices	Fresh fruits	Dry fruits	Vegetables	Other food crops	Oilseeds	Fibres	Dye and Tanning	Drugs narcotics and other plantation	Fodder
Andhra Pradesh	2%	4%	1%	6%	11%	22%	3%	0%	3%	5%	0%	3%	3%
Arunachal Pradesh	0%	0%	0%	0%	0%	0%	1%	2%	0%	0%	0%	0%	0%
Assam	2%	1%	0%	3%	2%	1%	3%	5%	1%	0%	0%	13%	1%
Bihar	5%	2%	3%	0%	2%	0%	5%	0%	0%	0%	0%	0%	0%
Chhattisgarh	4%	2%	1%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%
Goa	0%	0%	0%	0%	0%	10%	0%	0%	0%	0%	0%	0%	0%
Gujarat	3%	5%	3%	13%	9%	0%	3%	1%	10%	19%	0%	8%	14%
Haryana	4%	0%	2%	1%	1%	0%	1%	0%	3%	5%	29%	0%	3%
Himachal Pradesh	1%	0%	0%	0%	2%	0%	1%	0%	0%	0%	0%	0%	0%
Jharkhand	1%	0%	0%	0%	0%	0%	2%	0%	0%	0%	0%	0%	0%
Karnataka	5%	11%	19%	23%	8%	4%	7%	0%	6%	7%	0%	13%	6%
Kerala	0%	0%	0%	5%	7%	6%	1%	2%	2%	0%	0%	23%	3%
Madhya Pradesh	14%	17%	3%	8%	2%	0%	4%	2%	24%	4%	0%	0%	15%
Maharashtra	6%	18%	20%	3%	18%	34%	15%	0%	16%	31%	0%	1%	18%
Manipur	0%	0%	0%	0%	1%	0%	1%	0%	0%	0%	0%	0%	0%
Meghalaya	0%	0%	0%	1%	1%	2%	1%	0%	0%	0%	0%	0%	0%
Mizoram	0%	0%	0%	1%	1%	0%	1%	0%	0%	0%	0%	0%	0%
Nagaland	0%	0%	0%	0%	1%	0%	1%	0%	0%	0%	0%	1%	0%
Odisha	4%	2%	0%	0%	0%	0%	0%	50%	0%	0%	0%	0%	0%
Punjab	6%	0%	1%	0%	2%	0%	2%	0%	0%	2%	0%	0%	2%
Rajasthan	9%	20%	0%	20%	1%	0%	2%	0%	22%	6%	71%	15%	20%
Sikkim	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Tamil Nadu	3%	3%	2%	3%	7%	15%	5%	32%	3%	1%	0%	5%	2%
Telangana	5%	3%	1%	3%	4%	1%	1%	0%	1%	15%	0%	1%	4%
Tripura	0%	0%	0%	0%	1%	0%	1%	0%	0%	0%	0%	3%	0%
Uttarakhand	1%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Uttar Pradesh	17%	10%	42%	1%	9%	0%	16%	4%	5%	0%	0%	8%	4%
West Bengal	5%	2%	0%	3%	6%	2%	23%	0%	3%	4%	0%	6%	3%
Andaman and Nicobar Islands	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Chandigarh	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Dadra Nagar Haveli and Daman Diu	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Delhi	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Jammu and Kashmir	1%	0%	0%	0%	2%	2%	0%	2%	0%	0%	0%	0%	0%
Ladakh	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Lakshadweep	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Puducherry	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

While the deployment scenarios provide a structured estimate of AgriPV potential, they are inherently idealistic and should be interpreted with caution. These projections are based on assumptions regarding land availability, crop compatibility, and system configurations that may not fully align with on-ground realities. The theoretical potential, which assumes the use of all available cropland, results in an upper-bound estimate of 65.06 TWp—an aspirational figure unlikely to be realized due to legal, social, and practical constraints. The commercial potential, derived using similar allocation methods, yields a more moderate estimate of 6.43 TWp, though it still overlooks barriers such as fragmented landholdings and market dynamics. A more grounded scenario focuses on feasible crop types suited for early adoption, estimating a potential of 4.78 TWp. Narrowing further, prioritizing states with the largest areas of suitable cropland brings the estimate to 3.89 TWp. These scenarios are useful for framing the discussion around AgriPV deployment, but must be contextualized within broader socioeconomic, environmental, and policy considerations.

The Table 20 details the calculations determining the potential under the deployment scenarios presented in section 2.4.

Table 20 – Various potential deployment scenarios and their respective available area for each crop-type

Crop types	Theoretical potential		Commercial potential		Feasible crop-types		Feasible crop-types + States	
	Available area (ha)	TWp	Available area (ha)	TWp	Available area (ha)	TWp	Available area (ha)	TWp
Cereals	6,77,43,722.80	20.32	66,98,357.56	2.01	66,98,357.56	2.01	48,76,343.25	1.46
Pulses	1,71,36,067.98	6.85	16,95,140.56	0.68	16,95,140.56	0.68	16,29,110.98	0.65
Sugar	42,38,420.82	1.06	4,19,274.66	0.10	-	-	-	-
Condiments and Spices	28,61,509.84	2.15	2,83,067.35	0.21	2,83,067.35	0.21	2,41,130.79	0.18
Fresh fruits	28,97,613.30	1.16	2,86,638.79	0.11	2,86,638.79	0.11	2,14,202.81	0.09
Dry fruits	3,50,452.48	0.09	34,667.59	0.01	-	-	-	-
Vegetables	42,37,213.21	3.18	4,18,966.78	0.31	4,18,966.78	0.31	2,64,909.68	0.20
Other food crops	3,12,622.14	0.08	30,911.42	0.01	-	-	-	-
Oilseeds	2,06,62,330.54	8.26	20,43,048.01	0.82	-	-	-	-
Fibres	85,52,893.33	6.41	8,45,692.20	0.63	-	-	-	-
Dye and Tanning	38,610.70	0.02	3,817.75	0.00	-	-	-	-
Drugs narcotics and other plantation	18,93,169.92	0.76	1,87,192.68	0.07	-	-	-	-
Fodder	3,68,11,568.18	14.72	36,39,850.84	1.46	36,39,850.84	1.46	32,74,995.72	1.31
Total	16,77,36,195.25	65.06	1,65,86,626.19	6.43	1,30,22,021.88	4.78	1,05,00,693.23	3.89