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Feasibility of Agri-Photovoltaics in Indian Agriculture

Insights from Maharashtra and Himachal Pradesh for Potato and Apple Farming

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Contents

List of Abbreviations

AgriPV	Agriphotovoltaics
BAU	Business as usual
BNG	Biodiversity Net Gain
BtM	Behind the meter
CAGR	Compound annual growth rate
CEA	Central Electricity Authority
CO2	Carbon-di-oxide
D-REC	Distributed Renewable Energy Credit
ESIA	Environmental and Social Impact Assessments
FPC	Farmer Producer Company
FPO	Farmer Producer Organisation
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
GVA	Gross Value Added
GW	Gigawatt
Ha	Hectares
HP	Himachal Pradesh
HT	High tension
IEA	International Energy Agency
INR	Indian rupee
IRR	Internal rate of return
KII	Key Informant Interview
KW	Kilowatt
kWh	kilowatt-hour
m	Meter
MH	Maharashtra
MoA &FW	Ministry of Agriculture & Farmer Welfare
MoEFCC	Ministry of Environment, Forests and Climate Change
MoSPI	Ministry of Statistics and Programme Implementation
MW	Megawatt
NISE	National Institute of Solar Energy
NPV	Net Present Value
NSEFI	National Solar Energy Federation of India
PV	Photovoltaic
RIA	Rapid Impact Assessment
ROI	Return on Investment
SDG	Sustainable Development goals
SPCB	State Pollution Control Boards
SPIES	Solar Park Impact on Ecosystem Services
SWOT	Strength, Weakness, Opportunity, Threats
UK	United Kingdom
yrs	Years

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Executive Summary

The feasibility analysis for implementing Agriphotovoltaics (AgriPV) specifically targeting apple farming in Shimla and Kullu district of Himachal Pradesh and potato farming in Pune district, Maharashtra, explores its potential benefits and challenges across technological, environmental, and economic dimensions. This executive summary synthesizes the document‘s key insights, analysis results, and strategic recommendations.

AgriPV in India

AgriPV integrates solar energy generation with agriculture by using solar photovoltaic (PV) systems installed on arable land to produce both energy and food. Given India‘s vast agricultural base and commitment to renewable energy, AgriPV could enhance land-use efficiency and support India’s renewable energy goals. The dual-benefit approach aligns with India’s energy and agricultural needs, addressing both food and energy security while contributing to climate action goals. Although AgriPV shows great potential, it encounters significant challenges such as environmental concerns, high initial investment, and limited awareness among farmers.

Environmental and Biodiversity Considerations

A significant finding in the feasibility study is the absence of mandatory Environmental and Social Impact Assessments (ESIA) for AgriPV systems. Currently, solar projects in India are classified under the „white category“ by the Ministry of Environment, Forests, and Climate Change, exempting them from environmental clearance. This lack of regulation presents a risk to ecosystems, particularly in biodiversity-sensitive areas, as AgriPV systems could impact soil, water resources, and local habitats.

Moreover, AgriPV systems can potentially impact crop yields due to shading. For example, in Maharashtra, potato yield reductions are anticipated, indicating a need for careful crop selection and guidance for farmers to choose shade-tolerant crops compatible with AgriPV set-ups. Instituting ESIA and setting land-use and zoning regulations are recommended to minimize adverse environmental impacts. Additional studies focusing on suitable crops and efficient AgriPV design could help enhance compatibility between agricultural and photovoltaic needs.

Business Model Analysis

The study evaluates AgriPV business models—Farmer Owned, Developer Owned, Joint-Venture, and Behind-the-Meter (BtM). The BtM model emerged as the most viable option currently, but this model is targeted at food processing units or pack houses with larger electrical power demand.

Small and marginal farmers in India may face difficulties in adopting AgriPV due to small and fragmented landholdings, making grid interconnection a challenge. Most states mandate a minimum solar capacity of 500 kW for grid connections, limiting small-scale participation.

To overcome these hurdles, policies promoting small-scale AgriPV grid interconnection and targeted incentives for farmer groups like Farmer Producer Organizations (FPOs) are necessary.

The economic viability of AgriPV in India is hindered by low solar feed-in tariffs and high initial capital costs,

which discourage investment. Achieving a competitive return on investment (ROI) is challenging under current conditions, as the solar feed-in rates offered by public utilities will not permit an attractive return on investment. To make AgriPV more attractive to investors and farmers, the study suggests exploring additional revenue mechanisms, such as Distributed Renewable Energy Credits (D-REC), carbon credits and locational feed-in tariffs that account for grid benefits from decentralized power generation.
For farmers, the high initial costs of AgriPV are a significant barrier. Financial support through low-interest loans, and project-based financing could help mitigate this challenge.

Multidimensional Feasibility Assessment

The study also conducted a multidimensional feasibility poll among Indian AgriPV experts, highlighting both opportunities and obstacles across technological, policy, socio-cultural, ecological, economic, and financial dimensions. Expert opinions were mixed regarding AgriPV‘s technological and policy feasibility due to challenges with agricultural land access, power infrastructure, and limited regulatory clarity. Notably, there is a need for regulatory improvements to protect farmers‘ interests and support small-scale AgriPV systems. While the socio-cultural feasibility of AgriPV remains limited due to low awareness among farmers, educational initiatives could drive interest and acceptance. From an ecological standpoint, experts conveyed measured optimism, noting that while AgriPV presents opportunities to support biodiversity, its deployment requires meticulous planning and evidence-based strategies to prevent unintended ecological consequences

Strategic Recommendations

The feasibility analysis outlines several key recommendations to enhance AgriPV’s prospects in India:

1. **Policy and Regulatory Reforms:** Promote the introduction of mandatory ESAI for AgriPV projects and the development of zoning regulations to manage ecosystem impacts. Additionally, revising grid interconnection standards to support small-scale AgriPV installations would enable more smallholder participation.
2. **Financial Incentives and Support Mechanisms:** Increase solar feed-in tariffs for AgriPV-generated solar power to improve financial viability. Introducing D-RECs and offering subsidized financing or loans for smallholder farmers would alleviate capital investment burdens.
3. **Educational Outreach and Farmer Support:** Conduct educational programs to raise awareness of AgriPV’s benefits, especially in regions with a strong FPO presence. Highlighting the benefits of the BtM model and potential income diversification from energy sales could encourage broader acceptance.
4. **Research on Crop Compatibility and AgriPV Design:** Conduct extensive research on shade-tolerant crops and AgriPV designs that minimize yield impacts. This would provide data-driven guidance for farmers and ensure AgriPV systems are adapted to regional agricultural conditions.

While AgriPV holds potential for addressing India’s food and energy security challenges, its feasibility is contingent on supportive policy frameworks, financial incentives, and educational outreach to farmers. Technological and economic constraints currently limit AgriPV’s widespread adoption, especially among smallholder farmers. With targeted investments, regulatory adjustments, and strategic educational initiatives, AgriPV could become a transformative solution for sustainable agriculture and renewable energy generation in India.

Introduction

1.

As the world faces the intertwined challenges of energy access and food security, Agrivoltaics (AgriPV) offers an innovative approach by integrating solar energy generation with agricultural production. In India, where nearly half of the workforce is engaged in agriculture, AgriPV can potentially improve the land-use efficiency and help facilitate the transition to a low-carbon economy while tackling climate change and resource scarcity. However, it is crucial to critically assess its potential adverse effects on the environment, biodiversity, and traditional farming practices to develop a sustainably integrated AgriPV ecosystem in India.

Globally, over 1 billion people lack access to electricity, while 800 million suffer from malnutrition and starvation, making food security and energy two of humanity's most critical needs (UN-SDG 2023). Agriculture plays a vital role in the Indian economy, employing about 45.76% of the workforce in 2023, despite contributing only 15% to the country's Gross Value Added (GVA), with an average growth rate of 4.30% over the past five years (MoA & FW 2023). The sector is predominantly composed of small farms, with many small and marginal farmers holding less than 2 hectares. The average land holding has decreased from 1.15 hectares in 2010-11 to 1.08 hectares in 2015-16.

India's agricultural sector accounts for 80% of the country's total water use (ICAR 2019) and 17% of total electricity demand (MoSPI 2023), while contributing approximately 18% of India's greenhouse gas emissions (ICRIER 2018). Climate change is increasingly impacting the sector, with heat-waves, unseasonal rainfall, and longer dry spells resulting in reduced crop yields (Environmental Challenges 2022), highlighting the urgent need for a transition to a low-carbon economy.

In 2023, 70% of India's power needs were met by coal plants (MoSPI 2023). However, India has set a goal of achieving net-zero emissions by 2070 (PIB 2023) and aims to reach 500 GW of non-fossil fuel power generation capacity by 2030, primarily through solar and wind energy. Renewable energy systems face constraints related to land use and resource availability (solar irradiation, wind speeds). The substantial land demands of solar energy highlight the importance of innovative mitigation strategies to facilitate the transition to renewable energy. (Auroville Consulting 2023).

The concept of installing solar photovoltaic (PV) panels on agricultural land, known as Agriphotovoltaics (AgriPV), was first proposed by Goetzberger and Zastrow in 1982 (Fraunhofer Institute 1982). AgriPV has been claimed to address both food and energy security while contributing to climate commitments by allowing the simultaneous use of land for energy generation and crop production. AgriPV can be integrated in various configurations to complement existing land use. These include interspersing crops with solar PV panels, creating grazing areas between the rows of panels and crops grown beneath them. Elevated solar PV installations can accommodate taller crops with different configurations to maximize sunlight, or solar PV panels can be positioned vertically between crop rows. Additionally, solar PV panels have been integrated into greenhouse or poultry farms to provide shade while generating clean energy. The solar PV panels can be either fixed, single or have dual axis orientation to obtain maximum output from the PV system (SolarPower Europe 2024).

Since 2014, several countries, including China, France, Japan, the USA, Germany, Italy, and South Korea, have introduced policies to support AgriPV deployment. By 2023, the global AgriPV capacity had reached approximately 13 GW (TUEWAS 2023), compared to the overall global solar capacity of 1,552 GW (IREDA 2023). In India, there are currently 24 operational AgriPV installations with a total installed capacity of 10.50 MW (NSEFI 2023).

Despite the potential benefits of AgriPV systems, their impact on local ecosystems and biodiversity is not well-documented. Concerns include habitat loss due to land use, disturbances from the reflective surfaces of PV panels, changes in the micro-climate beneath the panels, soil compaction etc. As of 2024, solar and wind energy projects in India are not required to conduct environmental impact assessments, as the Ministry of Environment, Forests and Climate Change (MoEFCC 2023) has categorized them under the ‚white category' industries, exempting them from obtaining ‚Consent to Operate' from State Pollution Control Boards (SPCB). Therefore, feasibility studies for AgriPV systems should assess social, economic, environmental, and biodiversity impacts, facilitating development of mitigation strategies for any identified negative effects.

This assignment, conducted by the project Green Innovation Centres in Agricultural and Food Sector (GIC) India, aims to conduct a feasibility analysis of AgriPV systems for potato and apple farming in selected regions of Maharashtra and Himachal Pradesh. GIC is part of the Special Initiative (SI) 'Transformation of Agri-food Systems' (earlier SI 'One World, No Hunger'), of the Ministry of Economic Cooperation and Development (BMZ), Federal Republic of Germany. The project is being implemented by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), in collaboration with the Indian Ministry of Agriculture & Farmers Welfare (MoA&FW). It aims at contributing to sustainable rural development in the selected areas through innovations in the agricultural and food sector, including in the potato and apple value chains in Maharashtra and Himachal Pradesh respectively.

The study will evaluate the social, economic, and environmental impacts of AgriPV installations for apple farmers in Himachal Pradesh (Shimla and Kullu districts) and potato farmers in Maharashtra (Pune district). The findings will provide an evidence base to determine whether the technology is viable for small and marginal farmers in these locations. The target audience for this study includes international development organizations, policymakers, civil society organizations, think tanks, and solar developers interested in investing in AgriPV systems.

The study methodology consists of four primary tools. First, the literature review assesses environmental and biodiversity impacts, highlighting AgriPV's potential to support ecological health through soil quality and water management. The review categorizes (environmental and societal) impacts according to different categories of ecosystem services, such as provisioning, regulating, and supporting ecosystem services, with considerations for scale, agricultural practices, and location-specific ecological factors.

The SWOT analysis offers insights into AgriPV's strengths, weaknesses, opportunities, and threats by combining literature findings, business modelling, field visits, and expert interviews. This provides a comprehensive understanding of AgriPV's potential benefits and challenges for agriculture.

The business model evaluation explores four AgriPV ownership models: Farmer Owned, Developer Owned, Joint-Venture, and Behind-the-Meter, to determine optimal approaches for integrating solar systems on farms. Lastly, the multidimensional feasibility assessment analyses technological, policy, socio-cultural, ecological, economic, and financial aspects, presenting a thorough evaluation of AgriPV's viability for small land-holding farmers in these regions.

Current Status of AgriPV in India

2.

AgriPV is emerging as a potential solution to tackle India's intertwined challenges of food security and renewable energy, optimizing land use by combining agriculture with solar power generation. While still in its early stages, there are 24 documented AgriPV projects totalling a combined generation capacity of 10.57 MW.

AgriPV is an innovative approach to tackle the intertwined challenges of food security and renewable energy deployment in India. By combining agriculture with solar power generation, AgriPV offers a dual-use approach that optimizes land use, especially in a country where arable land is at a premium.

India's commitment to expanding its renewable energy capacity is evident through its ambitious targets, such as achieving 500 GW of renewable energy by 2030 (PIB 2023b). Solar energy, a cornerstone of this goal, presents challenges in land acquisition, given the competing demands for agricultural production, the preservation of natural landscapes and the creation of additional carbon sinks through reforestation efforts.

While it will be impossible to accurately predict the growth of solar energy and its land resource uptake over the next decades various estimates for the land area required for solar energy by the year 2050 are available. These range from a conservative estimate of 18,399 hectares for a 25% share of solar energy of the total energy generation to a more aggressive assumption of 93,204 hectares of land for 60% share of solar energy of total generation in 2050. A 93,204 hectare of land occupation represents about 2.80 per cent of India's total geographical area, equivalent to the current combined expanse of permanent pastures and other grazing lands. Agriculture today on the other hand uses up to 58% of the total geographical area of India (MoSPI 2023).

Table 1: Comparison of multiple estimates for land use by renewable energy technologies in 2050

REPORT	TOTAL (TWH)	SHARE OF SOLAR (TWH)	SHARE OF SOLAR	CAPACITY (GW)	MIN. REQUIRED AREA ('000 HA)	% ON TOTAL AREA	MAX. REQUIRED AREA ('000 HA)	% ON TOTAL AREA
CEA	5,072	1,265	25%	732	14,054	0.43%	18,300	0.56%
IEA STEPS	4,968	1,745	35%	1,033	19,384	0.59%	25,825	0.79%
IEA SDS	4,551	1,996	44%	1,176	22,579	0.69%	29,400	0.89%
IEA IVC	5,467	1,895	35%	1,135	21,792	0.66%	28,375	0.86%
Gulagi	7,212	4,441	62%	2,220	42,624	1.30%	55,500	1.69%
TERI/Shell	10,934	3,909	36%	2,300	44,163	1.34%	57,504	1.75%
CEEW	10,602	6,336	60%	3,728	71,580	2.18%	93,204	2.84%

Source: IEEFA 2021

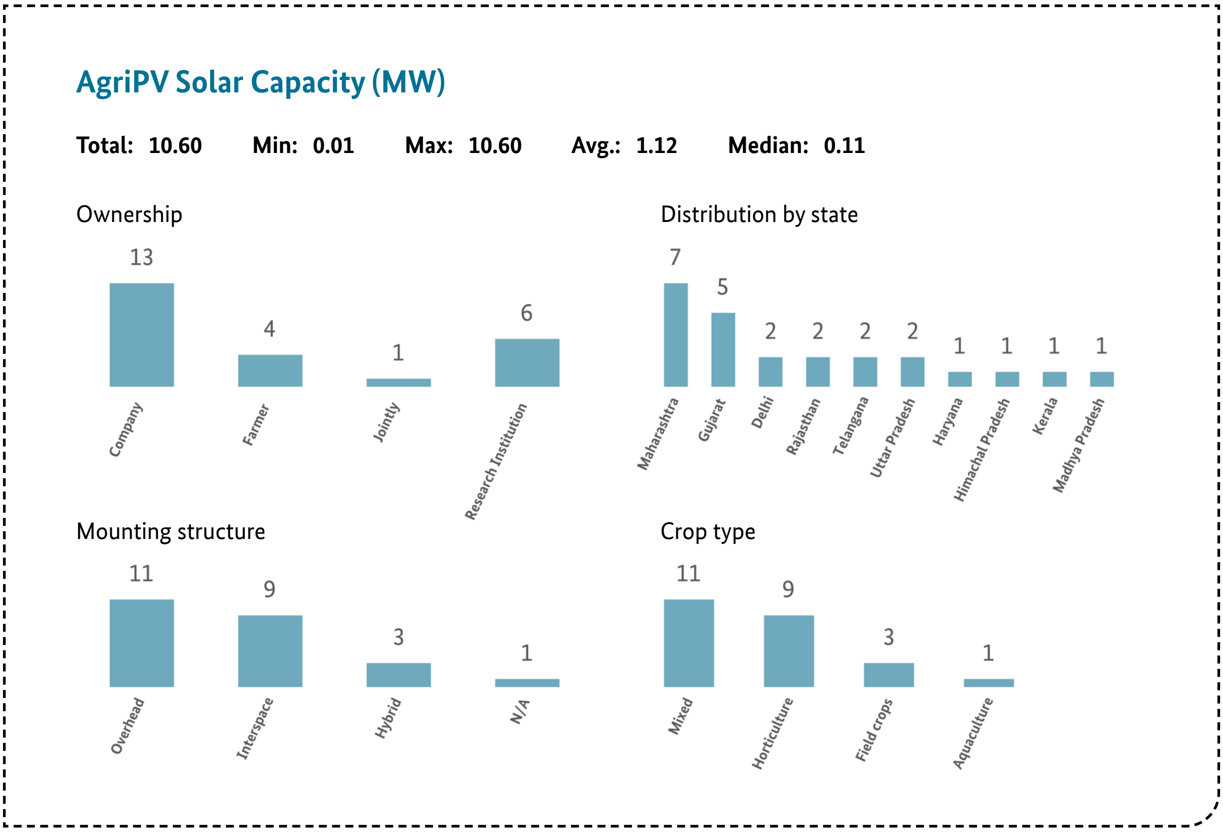
Table 2: India land cover

LAND CLASSIFICATION	AREA ('000 HECTARE)	Share of Area
Forests	71,751	21.83%
Area put to non-agri-cultural uses	27,777	8.45%
Barren & unculturable land	16,542	5.03%
Permanent pastures & other grazing lands	10,480	3.19%
Agricultural Land	1,79,993	54.75%
Total geographical area ('000 hectares)	3,28,726	100.00%

Source: MoSPI 2023b

AgriPV in India is still in an early stage. The integration of solar panels with crops like vegetables, fruits, and grains is being explored in several states. However, the success and widespread adoption of AgriPV in India faces several challenges. These include the high initial cost of installation, the need for technical expertise in managing both agricultural and solar power systems, and the potential for conflicts between agricultural practices and energy generation. As of August 2024, an estimated 24 AgriPV projects have been documented in India. Most of these systems are owned by private companies, with 13 out of 24 being company-owned. The total operational capacity is 10.57 MW, with a median capacity of 108 kW. Maharashtra and Gujarat lead with 50% of these systems. Overhead mounting structures are slightly more common, and horticultural crops are most prominent, with 9 systems dedicated to them. Only two systems currently cultivate potatoes, and none focus on apples.

Figure 1: Key stats: AgriPV in India



Assessment of Environmental and Biodiversity Impacts

3.

In the face of accelerating climate change and shrinking natural habitats, it is essential that agricultural and energy innovations do not contribute to environmental degradation. AgriPV system design is essential to ensure for positive environmental impacts. By focusing on biodiversity and ecosystem health, they can prevent harm while improving soil quality, boosting biodiversity, and aiding water regulation.

As climate change accelerates and natural habitats face increasing pressure, it is critical that new agricultural and energy solutions do not exacerbate environmental degradation. Instead, they should consciously integrate ecosystem and biodiversity considerations in the design, installation, and operation of AgriPV systems. Integrating these considerations ensures that AgriPV systems contribute positively to ecosystem health by promoting biodiversity, improving soil quality, and supporting water regulation. By prioritizing these elements from the outset, AgriPV systems can become models of sustainable development, demonstrating how renewable energy and agriculture can coexist and thrive while safeguarding the planet‘s ecological balance.

This chapter attempts a summary of the state-of-the-art research on biodiversity and ecosystem impacts of AgriPV. As AgriPV is an emerging technology, we also took reference from research on the impact of ground-mounted solar energy systems and linear infrastructure projects. The impact of AgriPV will vary depending on the size of the solar PV system, the type and intensity of agricultural practices, the prior land use, and the surrounding ecological context. Therefore, the below detailed impact statements should be considered with these factors in mind.

This chapter is divided into two sections: environmental and societal. The first section reviews the impact of AgriPV systems on ecosystem services, highlighting best practices and recommendations to minimize harm. The second section explores the social impact, focusing on community acceptance and potential job creation.

3.1. Environmental Impacts

3.1.1. Provisioning Services

Ecosystem provisioning services are the tangible benefits that humans derive directly from ecosystems. These services include the production of resources such as food, water, timber, fibre, ornamental resources, genetic resources and medicinal plants. They form the foundation of human survival and economic activity by supplying the raw materials needed for various industries and daily life (WRI 2023). The section below assesses the potential impact of AgriPV on three provisioning services, these are food provision and water provision.

3.1.1.1. Food Provision

AgriPV systems show mixed impacts on crop yields.

Studies on yield impact show wide variations in results. Studies in Germany and Japan found that leafy vegetables and legumes grow better under AgriPV, while rice and wheat yields decrease, and other crops show mixed results. (Gonocruz et al., 2021; Homma et al., 2016; Trommsdorff, 2021; Weselek et al., 2019). Pilots in India have only tested AgriPV systems with a limited variety of crops and agricultural settings. During the visit to the AgriPV plant in Delhi, wheat was replaced by leafy vegetables and turmeric - as they were found to be 'more' shade-tolerant - after the AgriPV system was introduced. Furthermore, the results from many of these pilots cannot be generalized as they are not controlled for other environmental variables. The lack of adequate data on crop growth factors like temperature, light flux, and humidity in the proximity of crops makes it challenging to identify the precise contribution of AgriPV design in crop growth and apply the learnings to a wider geography. Hence, the results so far can only be taken as suggestive of future designs. Further pilots with rigorous testing methods are needed to build a strong knowledge base for scaling up AgriPV systems.

"Traditional crops like rice and wheat are not well-suited to an AgriPV setup. However, AgriPV can be more suitable for high-value crops, providing farmers with the opportunity to generate additional income". (paraphrase from Key Informant Interview)

The installation of AgriPV systems can lead to a reduction in the available cultivation area and therefore decrease crop yield. The reduced cultivation area is mainly caused for accommodating the supports for the mounting structure. Yield decrease is also due to shading from the PV modules, with the impact varying depending on the crop type and climate. For instance, a study in Germany showed a 13% decrease in potato yield due to shading and area loss of 8.30% from the mounting structures (Wagner et al., 2023).

One benefit of AgriPV is that it can protect crops from weather hazards like hailstorms and reduce dust erosion and deposits on the panels (Weselek et al., 2019). Representatives from the AgriPV site in Parbhani, Maharashtra, shared a similar experience, where the AgriPV structure shielded the crops during a storm.

3.1.1.2. Water Provision

Poorly designed AgriPV systems can disrupt stormwater management.

Over-abstraction of surface and ground water can have negative impacts on ecosystem health and function, and cause lakes and rivers to become seasonally dry, with potentially negative impacts on human livelihoods, and reduce the provision of other ecosystem services. Agriculture is accountable for about 80% of water use in India (ICAR 2019). Infrastructure developments including the AgriPV system can

alter the natural stormwater flow and impact groundwater infiltration. Without a properly designed stormwater management system and a soil erosion and sediment control plan that follows best management practices, solar installations risk increasing surface runoff, which can destabilize landfill cap systems, expose underlying waste, and transport contaminated materials. (Great Plains Institute 2021).

"Drip irrigation leads to reduced water runoff and enhanced water-use efficiency. Additionally, installing rainwater harvesting systems in arid and semi-arid regions can ensure adequate water supply during dry periods." (paraphrase from Key Informant Interview)

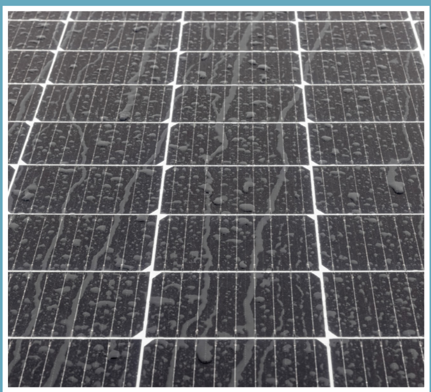
The introduction of an AgriPV system will require water for the cleaning of the solar panels. The water demand for solar PV can be considered to be moderate. The operational water withdrawal intensity of solar PV in India is around 0.08 m3/MWh (primarily related to panel cleaning), which is only 0.5% of the average for thermal power plants, while for wind energy, the water withdrawal is zero. (IRENA 2018).

During the site visit, it was observed that the overhead PV panels were regularly cleaned by spraying water. The runoff from this cleaning dripped onto the crops beneath the panels, potentially causing damage to them.

Using dry cleaning solutions for the cleaning of the panels can reduce the water demand for solar PV panel cleaning to zero. AgriPV systems on the other hand have the potential to increase water availability by lowering irrigation demand and protecting crops from the effects of extreme irradiation, such as sunburn and heat stress. (Jung et al. 2024).

"Solar PV panels were cleaned with RO-purified water to prevent scaling, with the water requirement estimated at 0.9m³ per MWh, which exceeds the amount suggested by research." (paraphrase from Key Informant Interview)

Water Provisioning - Good Practices



Stormwater Management in Solar Projects
The PV-SMaRT program offers a stormwater runoff calculator, available for free at PV-SMaRT Solar Runoff Calculator. This tool helps estimate runoff for various conditions, provides a solar-specific curve number for integration with other models, and includes a user manual for effective use. The PV-SMaRT program identified four essential factors for managing stormwater and enhancing water quality in solar developments:
Compaction: Addressing soil compaction and bulk density on site.
Soil Depth: Including soil depth in stormwater modelling and design.
Ground Cover: Using appropriate vegetated ground cover between and under solar arrays to improve infiltration.
Disconnection: Maintaining sufficient spacing between arrays to facilitate infiltration.

3.1.2. Regulating Services

Regulatory services for an ecosystem encompass the functions and processes that help maintain the balance, health, and sustainability of the environment. Regulating services include:

- Climate regulation
- Temperature regulation
- Water purification and waste treatment
- Erosion control
- Air quality maintenance
- Regulation of human disease
- Pollination
- Storm protection (WRI 2023)

3.1.2.1. Climate Regulation

AgriPV systems can offer low-impact development avoiding land-use changes that reduce carbon sequestration.

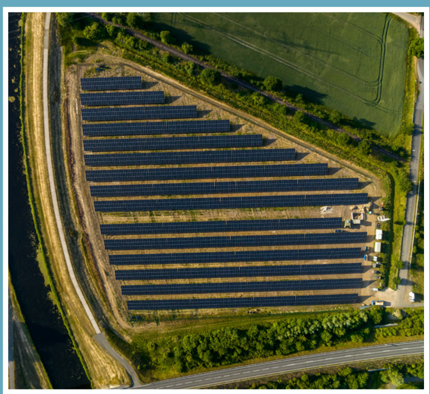
Climate regulating services are becoming increasingly important and existing carbon storage mechanisms including sequestration (both land and marine) are crucial in moderating the impacts of climate change. Land and marine ecosystems are responsible for absorbing approximately half of the human-generated greenhouse gas emissions. (Scholes., 2016).

On a local scale, land-use change can severely reduce the inherent greenhouse gas sequestration capability (Antonella De Marco et al., 2014). The deployment of solar energy systems, including AgriPV systems, can lead to detrimental land use changes, in particular if natural landscapes such as forests and grasslands are converted. The introduction of the AgriPV system into existing agricultural landscapes, without change of land use on and around the site, can be considered as low or no impact development in this regard. Installation of large-scale solar plants in forests would require clearing out the forest for the installation and further continually cutting or trimming the surrounding trees and plants to avoid shading effects. This hinders the high sequestration in the middle stage of tree growth, as they have to continually be trimmed. Further, a significant portion of the trimmings are converted to either firewood or burnt, leading to CO_2 emissions (Tawalbeh et al., 2020, Damon Turney et al., 2011).

According to the International Energy Agency (IEA), solar photovoltaic (PV) technology was essentially responsible for reducing CO_2 emission from electricity generation, as it contributed to 60% of the energy from recently installed renewable energy capacity, in 2023 (IEA-PVPS 2024). Life cycle emissions from solar PV systems are considerably low when compared to fossil-fuel-based systems (Turconi et al., 2013; Ludin et al., 2018; Bosmans et al., 2021) , with the majority of the systems emitting below 100 g CO_2 eq/kWh (Bosmans et al., 2021).

Climate Regulation – Good Practices

Zoning and Go-To Zones for Solar Energy
To prevent the loss and degradation of carbon sinks like grasslands and forests, some countries have implemented land use zoning policies or designated specific „go-to zones“ for solar energy development. Similar frameworks can be developed for AgriPV. For instance, Michigan University created a guide on planning and zoning for solar energy, designed to help communities prepare for solar energy integration by incorporating relevant requirements into their planning policies and zoning regulations. The guide demonstrates how various scales and configurations of solar energy systems can be integrated into different landscape settings, from rural to suburban and urban areas (Michigan University, 2021). It also provides a model zoning ordinance that local authorities can adapt. This comprehensive model addresses ground-mounted solar installations, building-integrated solar systems, and dual-use (AgriPV) applications. Additionally, it includes standards for the repowering and decommissioning of solar systems.



Solar land suitability assessment
In Italy, the government has developed guidelines for identifying suitable areas for renewable energy projects. Although legislative power lies with the regions, these guidelines offer a solid framework for designating „solar go-to areas.“ These zones benefit from simplified permitting procedures to encourage solar project development. Examples of go-to areas include:

- Land within 500 meters of industrial or commercial areas
- Areas within 500 meters of industrial plants
- Buffer zones within 300 meters of highways
- Areas near railways
- Abandoned mines and quarriesSites undergoing environmental remediation (Solar Power Europe, 2022).

3.1.2.2. Temperature Regulation

AgriPV systems can cause heat island effects while also reducing temperatures below the panels due to shading.

Incoming solar energy is either reflected back to the atmosphere or absorbed, stored, and later re-radiated in the form of latent or sensible heat. In natural ecosystems, regulation of temperature is maintained due to shading from vegetation. Solar PV systems have been found to reduce heat dissipation drastically causing the soil to retain heat and in turn increase in temperature (Barron-Graford et al, 2016).

> **"The installation of the overhead PV system at the AgriPV site in Delhi resulted in a 5°C decrease in temperature within the premises compared to the surrounding areas, fostering optimal growing conditions for the chosen crops." (paraphrase from Key Informant Interview)**

The introduction of solar PV systems on temperature regulation ecosystem services has both desired and undesired effects. The introduction of solar PV systems can lead to an undesired heat islanding effect that causes the ambient temperature to increase around the solar PV system, meanwhile also contributing to the reduction of temperature below the panel, owing to shading caused by the impervious nature of the panel (Yang et al., 2017). Night-time temperatures have been reported to increase by 3°C to 4°C (measured at 2 meters height, e.g. above the panels) in the solar PV facility as compared to the surrounding areas (Barron-Graford et al, 2016, Yang et al., 2017, Gómez et al., 2024). At the AgriPV site in Delhi, representatives reported that the overhead system lowered temperatures beneath the panels, creating an optimal environment for shade-grown crops like turmeric and leafy vegetables.

AgriPV systems help reduce heat impacts by using crops beneath the panels to regulate heat through evapotranspiration, while the elevated panels promote cooling through convection (Henry et al., 2023).

3.1.2.3. Water Purification and Waste Treatment

AgriPV systems may risk chemical contamination during panel cleaning or precipitation, impacting water purification services

Surface water contains dissolved substances and suspended matter of natural origins (inorganic and organic compounds). Natural purification is mainly carried out in the subsurface of the soil through filtration, sedimentation, oxidation-reduction, sorption-desorption, ion-exchange, etc (Balke et al., 2008).
Purification of surface and wastewater by vegetation is a form of ecosystem service. Natural purification processes are low maintenance, need low energy consumption and low mechanical technologies such as waste stabilization ponds or constructed wetlands. A combination of natural and engineering systems also offers useful solutions and aids in providing habitat for various species with minimum visual obstruction (G. Arampatzis et al., 2019).

The manufacturing of solar PV panels has also been observed to impact freshwater eutrophication and terrestrial acidification (Krexner et al., 2024). Additionally, leaching of the harmful chemicals such as cadmium, copper, lead, nickel, and zinc has also been noted during the operation phase of solar PV plants. The release of these chemicals can be attributed to manufacturing damage, damage during transport or damage during operation - from natural disasters or breakage of protective covers (Panthi et al., 2020). Even though rare, precipitation on damaged panels can also cause leaching of harmful chemicals and metals into the soil, air or groundwater (P. Sinha et al., 2015).

Accumulation of dust on solar panels can cause a decrease in the electricity production. Hence, cleaning of solar panels must be carried out periodically to maintain the maximum desired generation from the installed solar PV systems. In AgriPV systems, activities in the farm can result in soiling of the panels and result in loss of electricity generation and performance decrease during high production seasons, such as summer seasons (SolarPower Europe 2024). In the case of AgriPV systems, the impact on water purification service is not well researched. However, considering the use of solar PV panels and the growth of vegetation below the panels, it becomes critical to ensure no cross contamination of chemicals takes place during cleaning or is caused during precipitation as this could infiltrate the groundwater or water bodies in close vicinity and cause long-term effects.

Water Purification and Waste Treatment – Good Practices

Mitigation strategies for water purification
Enhanced packaging and careful handling during shipping and installation can reduce the likelihood of panel breakage, thereby minimizing the release of hazardous materials. Regular maintenance and inspections are essential to detect and repair damage early, preventing further degradation and potential leaching of harmful substances. Appropriate protection and stable structure to avoid damage due to heavy wind or hail, where applicable, must be ensured. To protect groundwater, installing barriers or liners beneath PV systems is crucial, especially in environmentally sensitive areas. Additionally, conducting leaching tests and risk assessments is vital to ensure the safety of the materials used in PV systems and to develop strategies that mitigate environmental risks. Water runoff from the panel can be collected and not allowed to drain through the soil or get exposed to the crops below the AgriPV system. The collected water can further be treated to be re-used for irrigation of the crops facilitating overall reduction of water use in the AgriPV farm.

Water quality for crops
Regular testing of water used for crops, whether in traditional agriculture or AgriPV, is essential to ensure it is free from heavy metals and impurities that could contaminate the crops. At the AgriPV site in Delhi, water from a nearby borewell was found to have high impurity levels, leading to the decision to source irrigation water from a borewell located 500 meters away. Consistent water quality testing helps minimize the risk of cross-contamination.

3.1.2.4. Erosion Control

Solar panels may increase erosion from runoff, but native vegetation can help control and reduce it. Research on solar farms and soil erosion is limited, but some models suggest that solar panels can increase erosion by directing high-energy runoff, particularly if the ground between panels is bare.
Additionally, the construction of solar farms involves land alteration that should be considered in erosion management, and further erosion caused by wind currents is a concern in arid areas with sparse vegetation (R. Yavari et al., 2022). As erosion affects the natural environment and threatens local water

security, strategies to control the erosion become critical. Larger-scale simulation models indicate that solar farms with native grasslands significantly reduce sediment export compared to agricultural land and turfgrass, though these models don't account for the elevated position of solar panels (Xiao et al., 2022).

"Drip irrigation was suggested as a strategy to mitigate soil erosion on the farm. Additionally, water runoff from the panels was directed to the crops below by utilizing drains."
(paraphrase from Key Informant Interview)

AgriPV can aid in controlling soil erosion and restoring surface vegetation without increasing land use intensity. Native grasses and forbs, with their deeper root systems, contribute to soil organic carbon accumulation, improve soil stabilization, and reduce water runoff. However, the impact of AgriPV on land with extensive soil erosion has not yet been explored extensively (Yang et al., 2019; Walston et al., 2022, Xiao et al., 2022).

Erosion control – Good Practices

Mitigation strategies for erosion control
During construction, minimizing soil compaction and disturbance is recommended to maintain natural runoff infiltration. Temporary erosion and sediment controls, such as erosion control socks, temporary sedimentation basins, or mulching, should be used (R. Yavari et al., 2022).

For long-term erosion management and to enhance infiltration, deep-rooted perennial vegetation like grasses, forbs, or legumes should be planted, either by preserving existing vegetation or through seeding. Crop production is possible but requires careful management to avoid increasing runoff or erosion during harvesting. Shade-tolerant plants can also be established under solar panels, and minimal mowing, pesticide, and herbicide use is advised (R. Yavari et al., 2022). Integrating photovoltaic and agricultural development with soil erosion management can offset the initially low returns of erosion control alone (Xiao et al., 2022).

3.1.2.5. Air Quality Maintenance

AgriPV systems, while having low operational emissions, can impact air quality during manufacturing & transportation and may reduce the ecosystem's natural ability to filter pollutants by altering land use and vegetation.

Air quality management in nature happens as ecosystems such as forests and wetlands naturally emit trace gasses in the atmosphere, which can combine with the existing precursors to form aerosols and other pollutants. The pollutants are further absorbed through depositing on or being intercepted by various vegetation in the surrounding area, such as trees, plants and soil. Nevertheless, in case this exchange exceeds the critical limit and falls out of balance, it could lead to adverse effects on other ecosystems as well as compromise the air quality (Smith et al., 2013, Pavel et al., 2013). AgriPV systems can impact the air quality maintenance ecosystem services by either diminishing the natural capability of the ecosystem to deal with air pollution or by increasing air pollution primarily during the manufacturing and transportation process of its components.

Solar PV systems indirectly impact the air quality primarily due to the release of particulate matter (PM) from the fossil-fuel electricity utilized in the manufacturing process. The impact of ambient particulate matter is serious as it has led to 1.67 million deaths in India in 2019, approximately 60% of the deaths being attributed to ambient particulate matter pollution. The European Environmental Agency estimated 0.39 million premature deaths in 2015 due to long exposure to air pollution (ISDBIA 2019, Agostini et al., 2020). Emissions of carbon monoxide (CO), methane (CH4), volatile organic compounds (VOC's), etc. - also collectively termed as tropospheric ozone precursors - can have negative impacts on human health and the ecosystem. In India, 0.16 million deaths were attributed to ambient ozone pollution in 2019. During the operation phase, solar PV systems contribute to much lower air pollution as compared to fossil-fuel electricity generation (Agostini et al., 2020).

Air quality has an indirect impact from the AgriPV systems caused by emissions related to manufacturing of solar PV panels. However, further studies can help identify the overall impact of the AgriPV system on air quality and the ability of the crops to aid in maintaining the natural cycle of the ecosystem.

Air Quality Maintenance – Good Practices

Mitigation strategies for air quality regulation
To reduce the impact on air quality of AgriPV systems several strategies can be implemented. Increasing local manufacturing and locally sourcing of solar PV components can minimize emissions from transportation and importation. Developing AgriPV systems can offset minor greenhouse gas emissions through vegetative carbon capture contributing to regulation of air quality. Employing cleaner manufacturing processes and low-emission transportation further reduces pollution. Additionally, incorporating advanced emission control technologies at manufacturing facilities, conducting regular air quality monitoring, and enforcing stricter emission regulations can help manage pollution. Implementing best practices for controlling ozone precursors also aids in reducing ground-level ozone. Together, these strategies contribute to improved air quality and a reduced environmental footprint.

3.1.2.6. Pollination

Pollination is crucial for ecosystems, food production, and livelihoods, but solar facilities can negatively impact pollinator communities.

Pollination plays a vital role in both human-managed and natural terrestrial ecosystems. Its importance as an ecosystem service is well recognized, providing various benefits such as food production, livelihoods for farmers and beekeepers, and cultural values. Approximately 87% of flowering plant species rely on animal pollination, which is crucial for maintaining the health and functionality of natural and agricultural systems, as well as ensuring crop production and food security. This service is especially critical for agriculture, as over 70% of global crops depend on animal pollination, with bees being the most effective and significant group of pollinators (Semeraro et al., 2018).

Solar energy facilities, particularly utility scale systems, can affect entire ecosystems. Factors such as land-use changes, habitat fragmentation and the use of pesticides and herbicides can contribute to the decline in pollinator communities (Semeraro et al., 2018). Infrastructure associated with solar PV facilities can influence pollinator fitness or movement and diversity and reduce predation by birds on insect herbivores or alter the nutritional composition of plants due to shading from panels (Moore-O'Leary et al., 2017).

While habitat restoration in agricultural landscapes is well-documented, integrating pollinator habitats within AgriPV solar projects is a newer concept that faces challenges related to vegetation management and compatibility with solar infrastructure. Emerging research suggests that partial shading from solar panels may benefit native plant growth and enhance insect diversity (Graham et al., 2021).

Pollination – Good practices

Introduce Pollinator Habitat
As a best practice, the farms visited in Kullu, HP, had implemented bee houses to house bees that assist in pollinating the crops. Typically, farmers rented bee houses during the flowering season, which increased their expenses. By installing bee houses on the farm, they promote effective farming practices.

Pollinator friendly regulation in US states
The preservation of agricultural land is essential for supporting pollinators, as plants like clover, which attract bees, also improve crop yields. The Solar Massachusetts Renewable Target (SMART) program offers incentives for solar projects that maintain agricultural use, and recently proposed a rate adder for pollinator-friendly solar developments. The University of Massachusetts is developing a certification program for such projects.

Other states also support the compatibility of solar and agriculture. For example, New Jersey allows agricultural land to keep a beneficial farmland assessment if certain conditions are met, and North Carolina offers tax penalties relief if solar developments maintain agricultural use. Vermont has a Pollinator Friendly Solar Generation Standard and additional guidance on integrating solar with agriculture (CESA 2024).

3.1.2.7. Storm Protection

AgriPV systems may reduce tree cover but can enhance storm protection for crops beneath them.

The presence of coastal ecosystems such as mangroves and coral reefs can dramatically reduce the damage caused by hurricanes or large waves. Similarly, forests and woodlands protect from storms. Insofar AgriPV development impacts these natural landscapes and directly reduces the land area under tree cover - the storm protection ecosystem service may be impacted negatively. On the other hand, an AgriPV system can protect the food crops grown under it from storms and extreme weather events, thereby significantly enhancing the local storm protection services for farming activities. Dedicated research on this topic could not be identified.

3.1.3. Cultural Services

Cultural ecosystem services refer to the non-material benefits ecosystems provide to societies, including cultural diversity, spiritual values, knowledge systems, education, inspiration, aesthetic values, social relations, cultural heritage, and recreation, with the following section exploring the potential impact of AgriPV on some of these services.

3.1.3.1. Cultural and Heritage Significance

Deploying renewable energy may affect cultural heritage, but regulations can help mitigate impacts.

The climate challenge imperative of deploying renewable energy systems at an unprecedented scale may impact the natural and cultural heritage, including architecturally sensitive areas, such as historical towns, historic buildings, and protected landscapes (Lucchi, E. 2022.) Policy guidelines and regulations can mitigate the potential negative impacts of introducing AgriPV in culturally sensitive landscapes.

3.1.4. Supporting Services

These are ecosystem services that support essential processes within ecosystems, such as providing habitats for plants and wildlife and preserving genetic and biological diversity. Examples include, but are not limited to:

- Habitat creation and maintenance
- Soil formation and management (WRI 2023)

3.1.4.1. Habitat Creation and Maintenance

The construction of AgriPV plants can alter habitats, threatening species and disrupting ecological processes.

Habitat alterations due to the construction of solar PV plants can occur at both the landscape and microhabitat levels. At the landscape level, habitat loss from PV installations can threaten various species, including reptiles, arthropods, bats, and birds. These changes occurring on account of solar deployment can further disrupt ecological processes, such as daily, seasonal, and migratory movements, by creating barriers like non-permeable fencing around PV sites (Gomez et al. 2024). At a microhabitat scale, solar PV plants create harsh environments that can be colonized by diverse microbial communities adapted to drought, heat, and radiation. They also introduce new shade and moisture gradients, altering microsite habitat conditions and affecting the species that thrive or decline in these new PV ecosystems. Future research should examine the impact of solar PV construction on the microclimate-soil-microorganism system, given its role in biological processes and ecosystem functioning (Gomez et al. 2024).

“Assessing the biodiversity impacts of AgriPV installations is challenging due to insufficient data, especially for smallholder farmers, highlighting the need for further research and real-world data collection.”(paraphrase from Key Informant Interview)

Few studies have examined the impact of utility-scale solar PV plants on animal fatality rates. The „lake effect“ hypothesis suggests that aquatic insects might mistake solar panels for water bodies due to polarized light reflections, potentially creating ecological traps (Horváth et al., 2010). This hypothesis may also apply to birds and bats and requires further research to verify its validity and understand how these organisms perceive solar energy infrastructure (Gomez et al. 2024).

While there is no dedicated research on the impact of AgriPV sites on bird populations, a recent study on utility-scale ground-mounted solar PV provides an estimate of bird and bat fatalities. The study found a mortality rate of 11.61 bird fatalities per megawatt per year (95% CI = 8.37–17.56) and 0.06 bat fatalities per megawatt per year (95% CI = 0.01–0.1). The research was conducted at 11 sites and focused solely on fatalities due to collisions with PV panels, excluding other mortality sources such as power lines and fences (Walston et al. 2016).

Solar PV panels can also influence plant communities. In water-stressed climates, solar PV panels can mitigate harsh conditions, enhancing seed bank survival and boosting plant productivity and diversity. However, in areas that benefit from rainfall and sunlight, PV panels can decrease photosynthesis and plant biomass, with the highest productivity and diversity occurring in runoff or interval zones between panels (Liu et al. 2023).

There is some early evidence that large-scale solar PV projects impact the diversity of arthropod pollinators and birds on-site. Arthropod pollinators (insect pollinators) utilize habitats both under the solar PV panels and in interval zones, though they tend to be less abundant and diverse under the panels. Solar PV parks may also show reduced bat activity and bird diversity and density, although bird reproductive success appears unaffected. Conversely, solar PV panels can provide perches, thermal refuges, and habitats for foraging, roosting, sheltering, and nesting, especially in desert environments (Gomez et al. 2024).

"EU regulations that require developers to create habitats to mitigate biodiversity loss could serve as a model for India, although implementation would need to consider the country's unique socio-economic and environmental conditions." (paraphrase from Key Informant Interview)

This suggests an opportunity to integrate natural habitats into ground-mounted solar PV plants and AgriPV sites by design. Incorporating natural habitats can include planting native, pollinator-friendly vegetation, creating water features, and designing elements that replicate natural habitats (Bungea et al., 2023).

Habitat Creation and Maintenance – Good Practices

Solar Park Impact on Ecosystem Services (SPIES)
To enhance biodiversity in solar parks, consider factors such as spacing between module rows, limiting tractor movement, and adding features like ponds, bird and bat houses, and hedges. The Solar Park Impact on Ecosystem Services (SPIES) decision-support tool can help identify the ecosystem service benefits derived from design and management strategies in solar installations (SPIES). SPIES decision support tool provides an accessible, evidence-based assessment of the impacts of solar park management on biodiversity, natural capital and ecosystem services for the UK solar industry. The framework includes an assessment of how solar park management practices affect ecosystem services, supported by scientific evidence.
Management strategies - effect of different management action strategies on ecosystem service provision.
Ecosystem services - Identifies management action to enhance specific ecosystem services.

Biodiversity Net Gain Legislation, UK
Under Part 6 of the Environment Act (2021) new developments in the UK are required to show a minimum net gain in biodiversity of 10%. Biodiversity Net Gain (BNG) applies to all new developments - including solar farms - and is designed so that a project 'leaves biodiversity in a better state than before'. BNG is calculated by a qualified ecologist by comparing the baseline biodiversity units - measured in its pre-development state - with the results that would be expected after construction is complete and all the ecological enhancements have been implemented. local authorities. This model zoning is quite comprehensive and addresses ground-mounted solar energy, building integrated solar, dual use (AgriPV) solar applications. It further includes standards for repowering and decommissioning of solar systems.

AgriPV installation at Alentejo site, Portugal
At the Alentejo site, an environmental impact assessment was initially conducted to evaluate the existing flora and fauna before project implementation. It was identified that a relationship exists between the black pig and the montado ecosystem (The Montado is an agro -silvo pastoral system explored at several levels – trees, bushes and herbs – according to the potential of each region) which is vital for sustaining native species and preserving biodiversity. Consequently, the black pigs were held in the zones with higher montado density. Additionally, to address visual impact, specific areas required screening, which was achieved using „green curtains" made from native trees like Arbutus unedo L. This species, which is useful for leather tanning, traditional medicine, and brandy production, also thrives in poor soils, is fire-resistant, and provides nectar for bees, fruits for birds, and winter shelter for insects.

3.1.4.2. Soil Formation & Management

Healthy soils are vital for food security, and ecosystems, but AgriPV construction can negatively impact soil quality.

Maintaining healthy soils is essential for sustaining agricultural productivity, ensuring food security, and supporting ecosystems. Healthy soils enhance crop resilience, improve water retention, and reduce the need for chemical inputs, thereby promoting environmental sustainability. They also play a crucial role in capturing carbon, which helps mitigate climate change. The construction of solar PV facilities can affect soil by altering its physical and chemical properties, with impacts varying depending on factors such as land-use history, vegetation management, and the characteristics of comparison sites. One key problem with the construction of AgriPV systems is the risk of soil compaction, which can then severely interfere with plant growth. Construction companies would use the same vehicles and machines for the construction of an AgriPV as they would use for the construction of regular ground-mounted solar plants (Wild and Schueller 2024). However, a similar degree of soil compaction may occur if heavy machinery is used for the farm operations.

> **"Combining regenerative agriculture practices with AgriPV can improve soil quality and support sustainable farming, aligning with the overarching objectives of environmental conservation and climate resilience."(paraphrase from Key Informant Interview)**

Conventional ground-mounted solar PV installations often degrade physical soil quality by reducing soil aggregate stability, which is important for soil function. Chemical soil quality in these facilities usually declines compared to semi-natural habitats, with decreases in organic carbon, total carbon, and total nitrogen, although these levels are comparable to those found in other human-altered soils, such as abandoned vineyards (Gomez et al., 2024).

Some studies suggest that chemical soil quality in solar PV facilities is degraded, showing reduced levels of organic carbon, total carbon, and total nitrogen compared to semi-natural habitats. However, these diminished levels are similar to those observed in other anthropogenic soils, like abandoned vineyards (Choi et al., 2020; Lambert et al., 2021). In contrast, vegetated PV parks have been found to have higher electrical conductivity, phosphorus, potassium, soil organic matter, and readily available potassium compared to bare land controls (Bai et al., 2022; Yuan et al., 2022).

On the other hand, it was suggested that PV panels in an AgriPV system can decrease soil erosion by up to 60% compared to traditional open-field agriculture. This is achieved by the PV panels mitigating impact of raindrops on the soil surface (Armstrong et al., 2014; Choi et al., 2020; Weselek et al., 2021).

Soil Formation & Management – Good practices

Good mitigation practices for soil management
Appropriate measures should be taken to restore the original soil structure during construction, and/or during the dismantling of the plant. The foundation of the Agri-PV system must minimize impacts on soil quality. Both when installing and dismantling the systems, there should be no negative consequence to the soil through compaction and land movement. In this regard, it is recommended to deploy the system when the ground is dry, using special tires and machinery, and/or moveable tracks. Agri-PV systems combined with crops should be deployed outside the growing season. Construction methods which provide secure foundations via removable fixtures in soil or soft ground should be used. In this regard, it is recommended to use a piling method, and to avoid the use of concrete or cementing whenever possible.

3.2. Societal Impacts

3.2.1. Energy Provision

AgriPV systems offer a dual solution of clean energy generation while supporting food production.

As of March 2024, India has an installed ground-mounted solar PV capacity of 69.11 GW (Niti Aayog 2024). With a growing population, expanding economy, increasing disposable income among consumers, and changing lifestyles, electricity demand is projected to quadruple by 2050 (TERI 2024). To achieve its decarbonization goals, India must increasingly rely on renewable energy sources,

"AgriPV set-ups encounter difficulties in selling electricity to DISCOMs because of inadequate connectivity, regulatory constraints, low feed-in tariffs, and DISCOMs' hesitance to provide the required permissions. Nevertheless, supplying electricity via open access was proposed as a potential alternative." (paraphrase from Key Informant Interview)

with solar energy expected to play a significant role in meeting both current and future electricity needs. Significant advancements in solar technology have fuelled the growth of solar energy in the global electric sector. Today, solar energy is one of the cheapest energy sources available, offering a carbon-free way to generate electricity (U.S. Department of Energy, 2021). AgriPV systems not only provide essential food production but also generate clean electricity, thus addressing the dual goals of energy and food security.

Synergistic benefits: increased energy output
The co-location of crops and solar panels can offer synergistic benefits. Temperature significantly impacts solar PV panel efficiency, with a 1°C increase causing a 0.6% decrease in efficiency when temperatures exceed 25°C (Barron-Gafford et al., 2019). During hot summer months, when PV panel efficiency plateaus, AgriPV systems with crops or native habitats can create cooler micro-climates under the panels, enhancing their lifespan and performance (Adeh et al., 2018; Barron-Gafford et al., 2019). These cooler micro-climates are plant-friendly and improve PV efficiency. Additionally, some AgriPV systems may reduce the net energy requirements of a solar facility by enhancing water use efficiency for plant irrigation. This can be achieved by repurposing water used for cleaning panels for irrigation or by reducing evapotranspiration through shading from the PV panels. (Hernandez et al., 2019).

3.2.2. Job Provision

AgriPV systems can support global decarbonization and boost rural economies through job creation.

> **"As the installation of AgriPV systems increases, there is potential for job creation in areas such as maintenance, operation, and crop production. " (paraphrase from Key Informant Interview)**

AgriPV systems have the potential to contribute to global decarbonization goals for the electricity grid while sustainably achieving various environmental, economic, and social objectives. Rural areas are ideal for solar energy development, and AgriPV projects can benefit rural economies by creating jobs and providing income diversification for farmers and landowners (Moore et al., 2021).

Job Provision – Good Practices

Employment generation for inmates
The Bardzour AgriPV farm, located at Reunion Islands, France, started operating in 2014. It integrates a variety of green technologies, including solar panels, energy storage, ground-mounted panels, and photovoltaic greenhouses. Inmates from a nearby prison cultivate crops on the farm, receiving training in sustainable agriculture practices as part of a social reintegration program.

3.2.3. Occupational Health and Safety

Agri-PV systems require careful maintenance and safe cable installation to ensure worker safety.

Special care is required when maintaining AgriPV systems, as people work on the site and as intensive agricultural use can take place, increasing the risk of damage and contamination. Farmers and workers should be informed about any specific maintenance needs or risks associated with the PV systems. Cables and cable trenches should be installed at a safe depth (of at least one meter) to avoid any damage caused by ploughs and other agricultural machinery. Good practice includes minimizing the number of cables in the ground. Instead, cable ways should be directed under module roofs, alongside the mounting structure (SolarPower Europe 2021).

Key factors influencing social acceptance include maintaining minimum distances from residential areas, careful site selection, and visual shielding. The successful integration of AgriPV systems into the landscape is crucial for their acceptance, highlighting the need to prioritize landscape considerations and conduct design research to address barriers to acceptance.
In Japan, regulations from the Ministry of Agriculture, Forestry, and Fisheries stipulate that AgriPV systems must not negatively affect land values or the efficient use of surrounding farmland. The income generated from electricity produced by AgriPV systems can support farm operators, helping to prevent farm closures and promote agricultural production and food self-sufficiency, thereby increasing social acceptance (Irie, N. et al., 2019).

Farm operators who have adopted AgriPV systems often report benefits such as stable income and sustained agricultural production. This contrasts with farmers who do not use AgriPV systems, as they may perceive potential negative economic impacts and reduced flexibility in land use. The size of AgriPV systems varies by country, influenced by factors such as cost-effectiveness, decentralization of energy generation, social considerations, and the impact on the farming landscape, all of which affect social acceptance. In Germany, smaller systems are generally preferred in the southern regions due to smaller land parcels, while larger systems are more practical in the north and east, where larger parcels are available (Irie, N. et al., 2019). Given the small and fragmented average landholdings in India, smaller AgriPV systems may be the more suitable option.

Social Acceptance – Good Practices

Photovoltaics Supporting Cultural and Community EcoSystem Services (PV-SuCCESS)
The US Department of Energy funding program targets improved social acceptance of PV and AgriPV installations by addressing landscape impact, aesthetics, and community concerns. PV-SuCCESS works to optimize system designs that are compatible with local agricultural practices and environmental conditions, ensuring that solar panels do not hinder farming activities. It also emphasizes stakeholder engagement, involving farmers, local communities, policymakers, and industry players to create mutually beneficial solutions. The program prioritizes research and innovation to develop cost-effective and efficient PV technologies tailored to different regional contexts. By fostering a collaborative approach and providing practical guidelines, PV-SuCCESS aims to facilitate the widespread adoption of agrivoltaics, contributing to renewable energy goals, sustainable agriculture, and rural development.

Figure 2: Summary of ecosystem service impact of AgriPV

Positive ○ Neutral ◑ Negative ●

3.1 Environmental impacts

3.1.1. Provisioning services

3.1.1.1. Food provision	◑	AgriPV systems show mixed impacts on crop yields.
3.1.1.2. Water provision	◑	Poorly designed AgriPV systems can disrupt stormwater water management.

3.1.2. Regulating services

3.1.2.1. Climate regulation	○	AgriPV systems can offer low-impact development avoiding land-use changes that reduce carbon sequestration.
3.1.2.2. Temperature regulation	◑	AgriPV systems can cause heat island effects while also reducing temperatures below the panels due to shading.
3.1.2.3. Water purification and waste treatment	●	AgriPV systems may risk chemical contamination during panel cleaning or precipitation, impacting water purification services.
3.1.2.4. Erosion control	●	Solar panels may increase erosion from runoff, but native vegetation can help control and reduce it..
3.1.2.5. Air quality maintenance	○	AgriPV systems can indirectly affect air quality by emissions during the manufacturing phase, though they produce much less pollution than fossil fuels during operation.
3.1.2.6. Pollination	●	Pollination is crucial for ecosystems, food production, and livelihoods, but solar facilities can negatively impact pollinator communities.
3.1.2.7. Storm protection	●	AgriPV systems may reduce tree cover but can enhance storm protection for crops beneath them.

3.1.3. Cultural services

3.1.3.1. Cultural and heritage significance	●	Deploying renewable energy may affect cultural heritage, but regulations can help mitigate impacts.

3.1.4. Supporting services

3.1.4.1. Habitat creation and maintenance	●	The construction of AgriPV plants can alter habitats, threatening species and disrupting ecological processes
3.1.4.2. Soil Formation & Management	●	Healthy soils are vital for food security, and ecosystems, but AgriPV construction can negatively impact soil quality.

3.2. Societal impacts

3.2.1. Energy provision	○	AgriPV systems offer a dual solution of clean energy generation while supporting food production.
3.2.2. Job provision	○	AgriPV systems can support global decarbonization and boost rural economies through job creation.
3.2.3. Occupational health and safety	◑	Agri-PV systems require careful maintenance and safe cable installation to ensure worker safety.
3.2.4. Social Acceptance	●	Public acceptance of AgriPV systems is affected by their height and visual impact on landscapes.
3.2.5. Educational opportunity and research	◑	AgriPV systems can negatively affect environmental education but may enhance research and educational services.
3.2.6. Recreational and tourism	◑	AgriPV systems may deter recreational activities but could attract eco-conscious visitors.

3.2.5. Educational Opportunity and Research

AgriPV systems can negatively affect environment but may enhance research and educational services. Education is one of the multiple services that ecosystems and landscapes provide to societies. Environmental education, both formal and informal, can lead to a better comprehension of the interactions between societies and ecosystems including many services provided by ecosystems to societies (Mocior and Kruse 2016). AgriPV will insofar impact these cultural ecosystem services as it negatively alters the landscape and contributes to a deterioration of the environmental quality and biodiversity. AgriPV system however has the potential to preserve or enhance the educational and research ecosystem services.

3.2.6.Recreational and tourism

AgriPV systems may deter recreational activities but could attract eco-conscious visitors
Insofar AgriPV systems or solar systems in general are perceived to impact the natural landscape negatively they may have a direct impact on the recreational and tourism services. However, tourism destinations may also have a unique selling point by sourcing their energy primarily from renewable energy sources and thereby attracting a more responsible and eco-friendly audience. Dedicated research on this topic could not be identified.

3.3. Conclusion

Experts agree that the environmental impact of solar PV systems, especially AgriPV, needs more research. There is a wide consensus among experts and researchers that a comprehensive understanding of the environmental impact of solar PV systems and in particular of AgriPV has not been established yet. While the benefits of solar energy as a clean and affordable source of energy are undisputed, its impact on critical ecosystem services and biodiversity merits more attention. This is crucial for achieving a sustainable energy transition that also prioritizes the protection and enhancement of ecosystem services and biodiversity conservation. Despite Asia and Europe leading in installed PV capacity (59.1% and 21.7%, respectively), much of the existing knowledge is based on research from North America, which only accounts for 12.3% of global PV energy installations (Gomez et al., 2024).

Recent international studies suggest that medium-sized PV plants result in greater loss of semi-natural habitats compared to large-sized plants. This discrepancy may be due to stricter environmental impact assessments required for mega-solar facilities, which can fragment larger projects (Gómez et al., 2024). However, this conclusion may not be transferable to the Indian context. A key finding of the feasibility study is the absence of mandatory Environmental and Social Impact Assessments (ESIA) for AgriPV systems. In India, solar projects are currently classified under the 'white category' by the Ministry of Environment, Forests, and Climate Change, exempting them from environmental clearance. This regulatory gap poses a potential risk to ecosystems, particularly in biodiversity-sensitive areas, as AgriPV systems may affect soil, water resources, and local habitats.

SWOT Analysis of AgriPV

4.

AgriPV offers a dual-use approach that enhances land efficiency by simultaneously supporting food production and renewable energy generation, creating opportunities for sustainable agriculture. However, challenges such as high upfront costs, limited awareness, and potential conflicts with traditional farming practices, concurrent landholding patterns and critical ecosystem services, must be addressed to ensure its sustainable adoption in India.

This section aims to comprehensively analyse the potential strengths, weaknesses, opportunities, and threats (SWOT) associated with implementing an AgriPV system. It identifies and evaluates internal and external factors that could influence the implementation and success of AgriPV in India. Strengths (S) and weaknesses (W) are considered internal factors that can be somewhat controlled, while threats (T) and opportunities (O) are regarded as external forces with limited control.

Figure 3: SWOT Analysis

	Positive	Negative
Internal	**STRENGTHS** • Enhanced PV efficiency • Increase in land use efficiency • Reduced evapotranspiration • Potential increase in crop yield • Protection of plants from high temperatures and extreme weather conditions • Diversification of the farmer's income	**WEAKNESSES** • Higher Upfront Cost • Limited Awareness of AgriPV • Reduction in cultivatable area • Decrease in crop yield • Technical constraints for farmers
External	**OPPORTUNITIES** • New markets and marketing opportunities • Local employment generation • Technological breakthrough • Ecosystem and biodiversity promotion	**THREATS** • Extreme weather vulnerabilities • Pest and disease risks • Economic viability • Land use conflicts • Lack of acceptance from farmers • Ecosystem and biodiversity impact

4.1. Strengths

Enhanced PV efficiency: The crops under photovoltaic panels would circulate cool air to reduce the temperature to make panels work optimally. High insolation, light winds, moderate temperature, and low humidity keep the panel's microclimate suitable for growing crops and increase panel efficiency (Ezzaeri et al., 2018)

Increase in land use efficiency: AgriPV systems significantly enhance land use efficiency by enabling the simultaneous production of food and renewable energy on the same plot of land. By integrating solar panels with agricultural activities, these systems maximize the utility of available land. Instead of dedicating separate areas for farming and energy generation, AgriPV allow for both co-existence, optimizing land resources in regions where space is limited or where land costs are high. This dual-use approach not only boosts the overall yield per unit of land but also contributes to the sustainability of both agricultural and energy sectors, making it a crucial strategy for meeting the growing demands for food and clean energy in a resource-constrained world.

"As the installation of AgriPV systems increases, there is potential for job creation in areas such as maintenance, operation, and crop production. " (paraphrase from Key Informant Interview)

Reduced evapotranspiration: AgriPV systems can play a crucial role in reducing evapotranspiration, the process by which water is transferred from land to the atmosphere through evaporation and transpiration from plants. By providing partial shading with solar panels, AgriPV systems lower the temperature and reduce direct sunlight on crops, which in turn decreases the rate of water loss from the soil and plants. This reduction in evapotranspiration helps conserve water, making it especially beneficial in arid and semi-arid regions where water scarcity is a major concern. The moderated microclimate created under the panels not only aids in water conservation but can also improve crop resilience to heat stress, leading to more sustainable agricultural practices in water-limited environments.

Potential increase in crop yield: AgriPV systems have the potential to increase crop yields by creating a more controlled and favourable microclimate for selected crops. The partial shading provided by solar panels can reduce excessive heat and protect crops from harsh sunlight, which can be detrimental to their development. This shading effect could help maintain soil moisture levels and reduces plant stress, particularly in hot and arid climates. Additionally, the panels could act as a shield against extreme weather conditions like hail or heavy rain, further protecting the crops. By optimizing the growing environment, AgriPV systems can lead to healthier plants and potentially higher yields, making this dual-use land approach an attractive option for enhancing agricultural productivity while simultaneously generating renewable energy.

Protection of plants from high temperatures and extreme weather conditions: The microclimate found under the solar panel can benefit crops since the PV shields them from excessive solar radiation and bad weather such as hail or strong winds. It also enhances the performance of the PV because the crops below create lower operating temperatures (Jamil et al., 2023).

Diversification of the farmer's income: The agricultural sector is facing an economic crisis. Farmers' incomes are low, and government assistance is becoming increasingly scarce. When crops are lost due to adverse weather, it can have devastating consequences for farmers who cannot generate profit from their agricultural operations. While a small financial compensation can help alleviate some of the system's constraints or address infrastructure issues, it's not a long-term solution. The business model for AgriPV systems is still under development and may change based on discussions with agricultural chambers. Some experts proposed a business model that involves renting land at very low rates to install solar panels above crops, protecting the crops. This approach is intended to be mutually beneficial, offering advantages in crop management for farmers.

"AgriPV has the potential to boost the livelihoods of smallholder farmers by facilitating high-value agriculture, with the economics of AgriPV being significantly influenced by the crop's growing cycle." (paraphrase from Key Informant Interview)

4.2. Weakness

Higher upfront cost: In an AgriPV system solar panels are suspended many feet above the ground, allowing crops to flourish or livestock to graze beneath. However, the main downside of AgriPV systems is the high cost of installation, compared to conventional ground-mounted solar PV systems.

The installation cost of an AgriPV system will also be higher because of the additional requirements of plant cultivation, irrigation, pumping, harvesting, and regular maintenance, which increase the operating costs. While AgriPV may generate additional income from crop sales the expected return on investment for an AgriPV system in India with the current solar net feed-in tariffs is prohibitive.

"Smallholder farmers may struggle to finance the AgriPV setup on their own due to insufficient financial resources." (paraphrase from Key Informant Interview)

"Farmers in both Himachal Pradesh and Maharashtra were not well-informed about AgriPV."(paraphrase from Key Informant Interview)

Limited Awareness of AgriPV: AgriPV systems are relatively new to many farmers. There is a need for proof of concept to demonstrate the potential benefits and viability of integrating these systems into agricultural practices.

Reduction in cultivatable area: The installation of solar panels reduces the cultivatable area available for traditional farming. The structures supporting the panels occupy physical space on the land, leading to a decrease in the area that can be used for crop production. Additionally, the shading created by the panels can further limit the growth of certain crops, affecting overall yield. While AgriPV systems aim to balance energy generation and agriculture, the reduction in cultivatable land can be a significant drawback, necessitating careful planning and crop selection to mitigate the impact on agricultural output.

Decrease in crop yield: While AgriPV systems offer many benefits, there is also potential for decreased crop yields due to several factors. The shading provided by solar panels, while beneficial in some climates, can limit the amount of sunlight that reaches certain crops, which is essential for their growth. Additionally, the physical presence of the panels and their supporting structures can restrict the movement of agricultural machinery and complicate traditional farming practices. This added complexity might result in suboptimal farming conditions, increased labour, and potential crop damage. These factors make it essential to carefully select crop types and design AgriPV systems to minimize potential negative impacts on agricultural output.

Technical constraints for farmers: The structure supporting the solar panels poses significant challenges for farmers. Once installed, the dimensions of the farmer's agricultural machinery cannot be altered, as the photovoltaic (PV) plant's design is tailored to the specific sizes of the machines in use. Additionally, farming around metal poles becomes more difficult, and irrigation systems must be adapted accordingly. The use of certain chemicals must also be carefully managed to prevent damage to the metal structure or panels. The elevation of the panels adds further complications, particularly for the operation and maintenance of the solar farm, as maintenance personnel must be authorized to work at heights. The combined management of agricultural and solar activities becomes considerably more complex with the implementation of an AgriPV system, necessitating adjustments to traditional farming practices.

Shade-intolerant crops: The selection of crops is restricted to varieties that grow well in low-intensity sunlight or are shade-tolerant. This limitation may restrict the capacity of the farmers to make crop cultivation choices based on the market demand.

4.3. Opportunities

New markets and new marketing opportunities: Being at the forefront of AgriPV development can also provide a significant marketing advantage, allowing these companies to differentiate their products by highlighting the sustainable and innovative methods used in their cultivation. This unique positioning can appeal to environmentally conscious consumers and open new avenues for premium branding and market differentiation.

Local employment generation: The installation and maintenance of AgriPV systems require specialized knowledge and skills, which can lead to job creation in the local economy. This can provide employment opportunities for residents and contribute to the growth of the local economy.

Technological breakthrough: Advancements in solar photovoltaic (PV) technology specifically designed for AgriPV systems are poised to accelerate the global deployment of AgriPV. Innovations such as semi-transparent panels, adjustable panel heights, and bifacial modules allow for more efficient integration with agricultural practices, enabling better light distribution and crop growth beneath the panels. These technological improvements help optimize land use by generating renewable energy while maintaining or even enhancing agricultural productivity. As these solutions become more accessible and cost-effective, they lower barriers to adoption, making AgriPV systems an increasingly attractive option for farmers and energy developers worldwide. This synergy between agriculture and renewable energy not only supports sustainable farming but also contributes to global efforts to transition to cleaner energy sources, driving widespread adoption of AgriPV on a global scale.

Ecosystem and biodiversity promotion: Well-designed systems can enhance biodiversity and create ecological corridors, potentially benefiting local wildlife and plant species (for greater details refer to Chapter 3.1).

4.4. Threats

Policy uncertainty: Policy uncertainty can significantly hinder the development of AgriPV systems by creating an unstable environment for investment and planning. When regulations and incentives related to AgriPV are unclear or subject to frequent changes, potential investors and stakeholders may face increased risks

> **"The need for clear definitions of AgriPV, along with a review of open access regulations, subsidy structures, and land-use policies, is crucial to address regulatory challenges and ensure the sustainable and equitable development of AgriPV in India, while also recognizing the growing importance of biodiversity." (paraphrase from Key Informant Interview)**

and uncertainties, making them reluctant to commit resources. This unpredictability can delay project initiation, inflate costs, and diminish the attractiveness of AgriPV compared to other energy or agricultural options. Additionally, without a consistent policy framework, the long-term benefits and financial returns of AgriPV systems become harder to project, further discouraging investment and innovation in this emerging field.

Extreme weather vulnerabilities: AgriPV systems might be susceptible to severe weather conditions like hail, heavy rain, strong winds, and snow. Such events can damage solar panels and crops, potentially resulting in reduced energy production and lower crop yields. (Kumpanalaisatit et al., 2022).

Pest and disease risks: The integration of solar panels into agricultural systems may create new micro-climates that could attract pests and diseases harmful to crops. This might lead to an increased reliance on chemical pesticides, which can have adverse environmental and health effects (Shukla et al., 2022).

Economic viability: The economic feasibility of AgriPV systems can be constrained by fluctuating crop prices. Furthermore, the regulatory and policy environment may not always be supportive of AgriPV development.

Land use conflicts: AgriPV systems necessitate substantial land for both agriculture and solar energy production. This requirement may lead to conflicts with other land uses, including urban development, natural habitats, or alternative agricultural activities.

Lack of acceptance from farmers: AgriPV projects will only succeed if they gain the support of farmers. Demonstrating the potential synergy between agriculture and photovoltaic energy requires maintaining crops alongside the panels, making farmers' expertise crucial to the project's success. However, farmers may be hesitant to embrace these projects due to the various constraints they introduce. A social study conducted in 2020 explored the acceptance of renewable energy projects in rural areas (Batel 2020). Interviews with farmers revealed key points of resistance. Many farmers lack trust in the technical aspects of these projects, citing the immaturity of the technology and the absence of proven, exploitable results to assure them of the project's feasibility. Another significant source of opposition stems from the disconnect between rural and urban communities. Farmers often feel that these renewable energy initiatives, driven by urban interests, are being imposed upon them without consideration for their perspectives. To overcome these challenges, better communication and greater involvement of farmers in the planning and execution of AgriPV projects are essential. This could help bridge the gap and foster a more collaborative approach.

Ecosystem and biodiversity impact: If not properly managed, the installation of solar panels may disrupt local ecosystems and wildlife habitats. The potential for unintended ecological consequences may include altering water flow or soil composition or reducing habitats for insects and birds (for greater details refer to Chapter 3.1).

Farm & Energy Sector profiling

5.

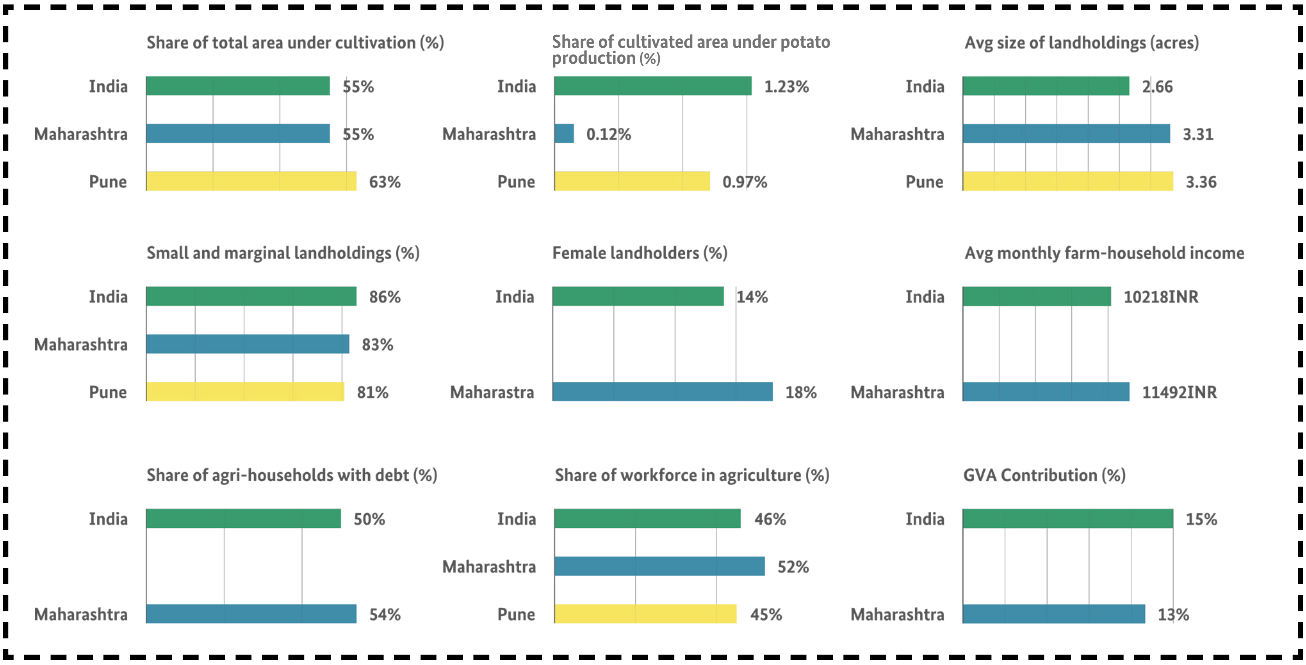
Potato farming in Pune district serves as a vital crop, with significant potential for growth despite challenges like fragmented supply chains and climate vulnerability. Similarly, apple farming in Shimla and Kullu districts is the backbone of the agricultural economy, but it faces serious threats from rising temperatures and climate change, underscoring the need for innovative solutions to ensure sustainability in these key sectors.

This section provides a high-level energy and farm sector profiling for the two areas of interest, apple farming in Himachal and potato farming in Maharashtra. The profiling intends to provide a high-level understanding of the farming in energy sectors in the respective geographies and inform the business modelling exercise in Chapter 6 of this report.

5.1. Potato Farming in Pune district: Farm Sector Profiling

Potato farming in Pune district, though modest in scale, plays a crucial role as a cash crop in areas like Ambegaon and Khed. Despite challenges such as fragmented supply chains and climate vulnerability, the sector holds significant potential through technological adoption and improved market access.

Figure 4: Data points farm profiling Pune district



5.1.1. Land Use and Potato Cultivation in India

Potato is the third most important food crop in the world after rice and wheat in terms of human consumption. India is the 2nd largest producer of potatoes in the world, with 44 million tons of production from about 2 million hectares, amounting to a productivity of 22 tons per hectare (ICAR 2024). The states of Uttar Pradesh, West, Bengal, Bihar, Gujarat, Madhya Pradesh and Punjab contribute more than 90% of total potato production in India. In Maharashtra, potato cultivation plays a less prominent role, an estimated 0.12% of the net cultivated area in the state is dedicated to potato cultivation. The state accounts for 0.46% of the country‘s total potato production (ICAR 2024). With 96km2 Pune district accounts for half of Maharashtra‘s area under potato cultivation. Within the Pune district, the potato crop is extensively grown as the principal cash crop in Ambegaon and Khed Tahsils.

5.1.2. Ownership and Female Participation

Maharashtra boasts 147 lakh operational land holdings, with an average landholding size per holding of 3.31 acres, surpassing the national average of 2.76 acres per holding. The average holding size in the Pune district increases to 3.36 acres per holding. Despite this, 81% of the district's landholdings are categorized as small and marginal farmers, slightly lower than the state average of 82.65% and the national average of 86.08%. Notably, female-operated landholdings in Maharashtra constitute 18.33%, exceeding the national average of 13.96% (Department of Economics and Statistics, 2023; MoAFW, 2019).

5.1.3.Household Income and Debt

In 2019 the average monthly household income for farm households in Maharashtra with INR 11,492 was slightly above the national average farm household income of INR 10,218. About 54% of agricultural households in Maharashtra are in debt, this is higher than the national average of 50.20% (MoA & FW 2023, MoAFW 2019).

5.1.4. Employment and GVA Contribution

In 2020, the agriculture and allied sectors contributed 15% to India‘s Gross Value Added (GVA), compared to 13% in Maharashtra. Despite the lower GVA contribution, 52% of the workforce in Maharashtra is employed in agriculture, significantly higher than the national average of 43%. The workforce employment rate in agriculture and allied sectors for Pune district is estimated at 45% (GIZ 2024). This high employment share underscores the sector‘s importance to the state‘s socio-economic welfare and development (MoA & FW 2023 and Department of Economics and Statistics 2023).

5.1.5. Key Challenges of the Potato Value Chain

Challenges include inadequate infrastructure for storage and transportation, fragmented supply chains, inconsistent quality standards, climate change-induced production risks, and pricing volatility. However, amidst these challenges lie promising opportunities. With a growing population and evolving consumer preferences, there is an increasing demand for processed potato products (ICAR 2024). Embracing technology adoption, enhancing value addition through product diversification, and leveraging policy support can further propel the sector forward. Moreover, improving quality standards and market access can unlock the export potential of Indian potatoes, contributing to both economic growth and agricultural sustainability.

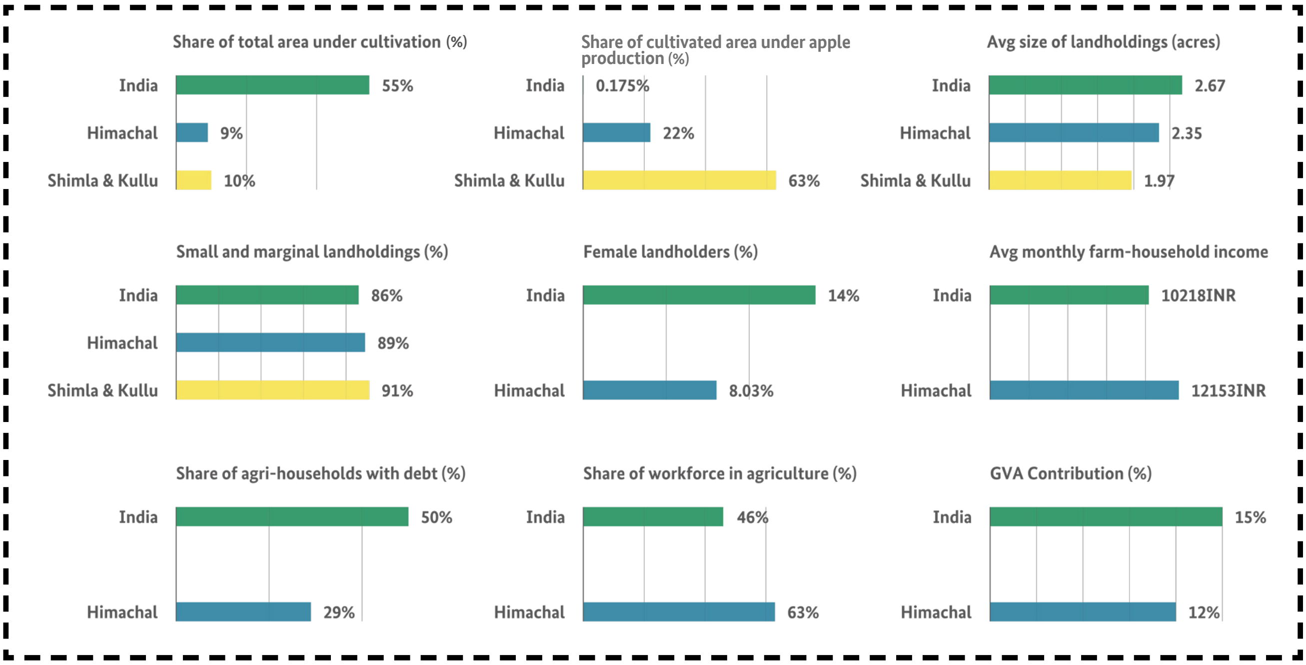
5.1.6.Climate Vulnerability

While Pune District may have a moderate climate vulnerability score (CEEW 2021), it remains highly susceptible to climate change. The region has witnessed a surge in extreme weather occurrences. From 1970 to 2019, drought events in Maharashtra spiked by 700%, while floods increased by 600%. Droughts adversely affect crops and livestock, whereas floods lead to substantial losses in various livelihood assets and standing crops. Furthermore, heightened monsoon rainfall is expected to intensify nitrate leaching and disrupt the decomposition of organic matter. Recent temperature and rainfall fluctuations, along with future forecasts, indicate a clear impact on crop productivity, including that of potatoes (GIZ, 2024).

5.2. Apple Farming in Shimla and Kullu Districts: Farm Sector Profiling

Apple farming is the backbone of the agricultural economy in Shimla and Kullu, contributing significantly to Himachal Pradesh's cultivation landscape. However, rising temperatures and climate change pose serious threats to productivity, with increased hailstorms and heat impacting fruit quality and yields.

Figure 5: 1 Data points farm profiling Shimla and Kullu districts



5.2.1. Land Use and Apple Cultivation in India

Apple production is India's fourth most significant fruit crop, following mango, citrus, and banana. The diverse agro-climates in India make apple cultivation particularly profitable in hilly states such as Arunachal Pradesh, Jammu and Kashmir, Uttarakhand, and Himachal Pradesh. These states contribute 95% of the total apple production in the country (Wani & Songara, 2018). Approximately 10% of the state's total geographical area is under cultivation in Himachal Pradesh. The state has become a leading producer of fruits and off-season vegetables, with apples being the dominant crop. About 21.87% of the cultivated area in Himachal Pradesh is dedicated to apple cultivation.

The state accounts for about 1,150 km^2 or 36.63% of India's apple cultivation area (Department of Economics and Statistics 2023). In Kullu and Shimla, two major apple-producing districts in Himachal Pradesh, this share rises to 63.36%. Apple farming is the backbone of the agricultural economy in these districts.

5.2.2. Ownership and Female Participation

Himachal Pradesh has 9.97 lakh operational land holdings, with an average size of 2.35 acres per holding, smaller than the national average of 2.76 acres. The average holding size in Kullu and Shimla districts is even smaller, at 1.97 acres. Kullu district has an average land holding size of 1.28 acres. Small and marginal landholdings constitute 91.27% of the total in Kullu and Shimla, higher than the state average of 88.85% and the national average of 86.08%. Female-operated landholdings in Himachal Pradesh stand at 7.43%, below the national average of 13.96% (Department of Economics and Statistics 2023 and MoAFW. 2019).

5.2.3. Household Income and Debt

In 2019, the average monthly household income for farm households in India was INR 10,218, this is significantly lower than the national average household income of Rs. 26,667. In Himachal Pradesh, the average monthly household income for farm households was INR 12,153, 18% above the national average. About 29.20% of agricultural households in Himachal Pradesh are in debt, much lower than the national average of 50.20% (MoA & FW 2023, MoAFW 2019).

5.2.4. Employment and GVA Contribution

In 2020, the agricultural sector contributed 15% to India's Gross Value Added (GVA), compared to 12% in Himachal Pradesh. Despite the lower GVA contribution, 63% of the workforce in Himachal Pradesh is employed in agriculture, significantly higher than the national average of 43%. This high employment share underscores the sector's importance to the state's socio-economic welfare and development (MoA & FW 2023 and Department of Economics and Statistics 2023).

5.2.5. Key Challenges of the Apple Value Chain

Despite the high production value, the average return on apple production remains low. Contributing factors include limited access to quality planting materials, farming equipment, chemicals, and irrigation infrastructure. Planting materials are typically sourced from accredited nurseries (NIAM, 2018). Apple farmers also lack marketing knowledge and rely on middlemen, who often offer lower prices than the prevailing market rates (OWFI, 2013). Exports remain the primary market for Indian apples. In 2017-18, India exported an estimated 12,500 tons of apples, with Nepal accounting for 71% and Bangladesh 28% (Alvarado & Mishra, 2018).

5.2.6. Climate Vulnerability

Apple production is highly sensitive to climate change, with temperature increases and precipitation variability posing significant risks. High temperatures and hailstorms are key climate hazards affecting the apple value chain. Rising temperatures cause issues like cracked apples and sunburn, reducing fruit quality. In the past 25 years, Kullu and Shimla have observed a 1.2°C temperature increase (Sen et al., 2015), leading to a 40-50% decline in regional apple productivity (Singh et al., 2016). Higher temperatures reduce the chill units necessary for budding, with a positive relationship between apple productivity and cumulative chill units. Thus, rising temperatures have led to a 0.4 tons/ha decrease in productivity. Temperature fluctuations also increase the frequency of hailstorms, which can cause severe damage to apple crops, break branches, inhibit growth, and reduce fruit sets in subsequent seasons (GIZ 2023).

5.3. Maharashtra – Energy Sector Profiling

Maharashtra's energy sector is heavily reliant on thermal power, but the state is rapidly expanding its focus on solar energy, aiming to more than double its current capacity by 2025. Despite ambitious targets, slow progress in initiatives like the KUSUM-A scheme indicates a need for stronger regulatory and policy support to accelerate solar adoption, especially in agriculture.

Table 3: Key data points:

CATEGORY	VALUES
Share of RE on total demand	18%
Installed Solar Capacity (MW)	6,250
Solar energy target 2025 (MW)	12,930
Kusum A sanctioned capacity (MW)	22.45
Kusum A installed capacity (MW)	2
Green Open Access Regulations	Yes
Preferential tariffs for solar (INR/kWh)	3.01

Maharashtra Power Sector Maharashtra's electricity generation is predominantly fuelled by thermal power, with coal-based plants making up a significant portion of the state's energy mix. However, in recent years, the state has been increasingly focused on boosting its share of renewable energy, particularly solar power. Despite setting an ambitious solar energy target of 12,930 MW by 2025, the current installed capacity of 6,250 MW highlights the need for accelerated efforts to meet this goal (Niti Aayog 2024). Currently, renewable energy accounts for 18% of Maharashtra's total electricity demand, with solar energy playing a central role in the state's expansion plans. The state aims to more than double its installed solar capacity by 2025.

The introduction of Green Open Access Regulations has made it easier for industrial and commercial consumers to access renewable energy, supporting a more decentralized and sustainable energy system. These regulations allow consumers with a sanctioned load of 100 kVa or greater to procure renewable energy directly from the open market.

To further encourage investment in solar power, Maharashtra has established a preferential feed-in tariff of 3.01 INR/kWh for solar systems with capacities below 10 MW. However, given the higher expected capital costs for AgriPV systems, the feed-in tariff of 3.01 INR/kWh may not provide an attractive return on investment.

The state initially targeted a total solar capacity of 22.45 MW under the KUSUM-A scheme, which promotes ground-mounted solar on agricultural land. As of 2024, only 2 MW of this capacity has been installed (MNRE 2024).

The limited success of the KUSUM-A scheme and the slow progress in achieving the state's solar energy targets suggest that further regulatory and policy enhancements are needed to create a more conducive environment for AgriPV systems to flourish.

5.4. Himachal Pradesh – Energy Sector Profiling

Hydropower remains the dominant source of energy in Himachal Pradesh, contributing 70% of its electricity demand, but the state is steadily increasing its focus on solar energy. With an ambitious target of 500 MW solar capacity by 2024, challenges like the absence of Green Open Access Regulations and early-stage solar expansion could slow renewable energy adoption.

Table 4: Key data points: Himachal Power Sector

CATEGORY	VALUES
Share of RE on total demand	70%
Installed solar capacity (MW)	95.23
Solar energy target 2024 (MW)	500
Kusum A sanctioned capacity (MW)	100
Kusum A installed capacity (MW)	700
Green Open Access Regulations	No
Preferential tariffs for solar (INR/kWh)	3.50 (up to 1 MW) 3.47 (1 to 5 MW)

Hydropower remains the cornerstone of Himachal Pradesh's electricity generation, contributing the bulk of the state's energy supply. However, solar energy is gradually becoming an important component of the energy mix. The state has an installed solar capacity of 95.23 MW, with plans to significantly increase this capacity to 500 MW by 2024.

Key Challenges

The electricity sector in Himachal Pradesh faces several challenges:

i. Environmental and Social Impacts: The development of large hydropower projects has raised environmental concerns, including deforestation and the displacement of local communities.

ii. Solar Energy Expansion: While the state has ambitious targets for solar energy, the expansion is still in its early stages. The installed solar capacity is only 95.23 MW against the 2024 target of 500 MW.

iii. Lack of Green Open Access Regulations: The absence of Green Open Access Regulations in the state restricts the broader adoption of renewable energy by industrial and commercial consumers.

Progress with Renewable Energy (RE) Integration

Himachal Pradesh is a leader in renewable energy integration, with 70% of its electricity demand met by renewable sources, primarily hydropower. Solar energy, though currently a smaller share, is poised for growth. The state has sanctioned 100 MW under the Kusum A scheme and remarkably installed 700 MW, showing significant progress in this area.

The state has also implemented preferential tariffs for solar energy, set at INR 3.50/kWh for projects up to 1 MW and INR 3.47/kWh for projects between 1 to 5 MW, to encourage the adoption of solar power. However, the absence of Green Open Access Regulations may hinder the full potential of renewable energy deployment.

Overall, while hydropower continues to dominate, Himachal Pradesh is making concerted efforts to increase its solar capacity and further its commitment to renewable energy, aiming for a more sustainable and resilient energy future.

Business Models for AgriPv

6.

The business modelling exercise evaluates the commercial feasibility of AgriPV systems for smallholding farmers, offering insights into investment, operational responsibilities, revenue-sharing, and expected returns.

This chapter explores various business models designed specifically for AgriPV systems in the contexts of apple farming in the Kullu and Shimla districts, as well as potato farming in the Pune district. The primary aim of the business modelling exercise is to assess the commercial feasibility of AgriPV systems for smallholding farmers. This analysis provides valuable insights into investment requirements, operational responsibilities, revenue-sharing mechanisms, and expected returns. For both apple and potato farming communities, four distinct business models are evaluated, which are detailed below.

Table 5: Business models

	SALES OF ELECTRICITY						SELF-CONSUMPTION	
	1. Farmer-Owned Model: In this model, the farmer assumes responsibility for both the investment in the solar PV system and the management of agricultural activities. This gives the farmer complete control but also places the full financial risk on them.		**2. Developer-Owned and Operated Model:** In this scenario, the developer handles the installation and operation of the solar PV system, while paying the farmer a land lease. The farmer continues to manage crop cultivation and retains the income from farming.		**3. Joint Venture Model:** The farmer and the developer establish an AgriPV company. The farmer contributes equity in the form of agricultural land, while the AgriPV company manages both the solar PV system and agricultural operations. Profits are distributed based on each partner‘s equity share in the company.		**4. Behind-the-Meter Model:** In this approach, a Food Processing unit leases lands and invests into an AgriPV system. It self-consumers the solar energy generated. It benefits from the avoided power purchase cost and from the farming income. A farmer is employed to perform the farm management.	
	Developer	**Farmer**	**Developer**	**Farmer**	**Developer**	**Farmer**	**Developer**	**Farmer**
Initial investment	-	✓	✓	-	✓	✓	✓	-
Agriculture - Responsibility	-	✓	✓	✓	✓	✓	✓	✓
PV system - Responsibility	-	✓	✓	-	✓	-	✓	-
Revenue from Solar	-	✓	✓	✓	✓	✓	✓	-
Revenue from Agri.	-	✓	-	✓	✓	✓	✓	-
Revenue from Land	-	-	-	✓	-	-	-	✓

Case study: Behind-the-Meter Business model
The 250kW AgriPV project at Sahyadri Farms in Nashik has pioneered the Behind-the-Meter (BtM) AgriPV business model, effectively combining agriculture with solar energy generation. Managed by Sahyadri Farms, one of India's largest farmer cooperatives, this project aims to reduce the energy costs for Sahyadri's food processing unit, enhancing operational efficiency through renewable energy. As a pilot initiative, it demonstrates a scalable model for deploying AgriPV systems in India, highlighting the potential for dual land use to benefit both agriculture and energy needs.

The financial modelling assumptions were made with careful consideration of the agricultural profile, power sector policies, and regulations specific to each geographical focus. Agricultural and electricity regulations for these regions were profiled, incorporating factors such as land costs, crop productivity, and feed-in tariffs. This ensures that each business model is tailored to the unique conditions of the crops and regions, enhancing both practicality and relevance.

The business model envisions the installation of an overhead AgriPV system on the average landholding of farmers in the region. The land area required varies based on the configuration chosen for the respective crops—apples and potatoes. The overhead bifacial solar PV panels are arranged in a shed structure, with details on the shed's dimensions and arrangement provided in Annexure 10.3.

The assumptions for the simulation are based on data from research and field visits to Pune, Maharashtra, and Kullu, Himachal Pradesh. Performance data for the AgriPV system was also sourced from research and visits to existing AgriPV farms. A detailed list of assumptions is included in Annexure 10.4 for reference.

Traditional farming productivity data was gathered from site visits and compared with research data. Crop productivity for apples and potatoes was primarily sourced from research studies and field visits in Maharashtra and Himachal Pradesh. Land values were established through on-site visits and discussions with farmers and representatives of Farmer Producer Organisations (FPOs), reflecting the most commonly observed case. The business models are built around two key parameters: (i) control of revenue streams from solar, land, and farming, and (ii) the route to market for the sale of electricity. The following options are considered for market strategy:

- Sales to electricity utilities at prevailing solar feed-in tariffs
- Sales to third parties via the Green Open Access/Open Access route
- Self-consumption of solar energy through net metering or captive power generation mechanisms

Open Access or Green Open Access allows power generators to sell ‚green' power to eligible third parties. To qualify under Open Access rules, a consumer must have a sanctioned load exceeding 1 MW. Green Open Access, which lowers the eligibility threshold to 100 kW, is limited to renewable energy sources. However, not all Indian states have introduced Green Open Access. Himachal Pradesh has not yet passed its Green Open Access Rules, while Maharashtra has. Typically, sales of electricity via Open Access or Green Open Access routes achieve higher tariffs per kWh than sales to electricity utilities, yielding better financial returns for developers. Under the self-consumption model, the financial return of the AgriPV system depends on the avoided power purchase cost. Simply put, if the cost per kWh from the AgriPV system is lower than the cost of grid power, the system will result in financial savings.

The primary goal of the business model analysis is to assess the economic feasibility of AgriPV for farmers and identify which model yields the highest revenue. Key outputs include the minimum solar feed-in tariff, revenue shares for both farmers and developers, comparisons of farmer revenue with business-as-usual (BAU) farming, contributions from multiple revenue streams, and net revenue from solar energy versus ground-mounted solar installations. The analysis also determines the solar feed-in tariff required to achieve an internal rate of return (IRR) of 14%. In Behind-the-Meter business model, where the FPO acts as the developer and consumes the generated electricity, the minimum industrial tariff needed to achieve the required IRR is determined. It is also assumed that the energy generated is consumed for pre and post-processing of agricultural produce from the farm.

Additionally, sensitivity analyses were conducted to assess the impact of various parameters on key financial metrics like IRR. Changes in capital costs and feed-in tariffs were examined to evaluate their influence on IRR. The analysis also incorporated the Distributed Renewable Energy Certificate (DREC) scheme as an additional revenue stream.

6.1. AgriPV Business Models for Potato Farming

In this section, the assumptions considered for the business model simulation will be detailed before discussing the results and observation from the simulations. The key assumptions for the modelling exercise are provided below (Table 6). For a complete listing of assumptions refer to Annexure 10.4. The assumptions considered were based on the literature research, key informant interviews with experts and data collected during site visits.

Table 6: Assumptions considered for business model – Potatoes

Assumption	Value
Solar PV system capacity	0.63 MW
Height of the system	5.00 m
Row distance between shed	5.00 m
Capital cost (AgriPV)	INR 3,21,61,500/-
Solar feed-in tariff	3.01 INR/kWh
Average productivity per acre (AgriPV)	7.00 MT
Net revenue per acre (AgriPV)	INR 3,15,000/-
Rent per acre	INR 60,000/-
Land value per acre	INR 50,00,000/-

The average landholding of a farmer was assumed to be 2.00 acres. It was estimated that an overhead AgriPV system of 0.63 MW could be installed in the available area with the selected arrangement. The overhead system is assumed to be of 5.00 m height and a particular arrangement has been adopted to facilitate the optimum sunlight required and maximum use of the available land. The details of the configuration are mentioned in Annexure 10.3 for further reference.

In the case for potato farming under AgriPV conditions, it was assumed that the productivity reduces as compared to traditional farming. The reduction was considered taking inputs from existing research and data collected from site visits. A reduction of 30% in productivity is considered with an added assumption of a 10% reduction in available land due to installation of the overhead PV system.

6.1.1. Results and Observations

Prevalent feed-in tariff:

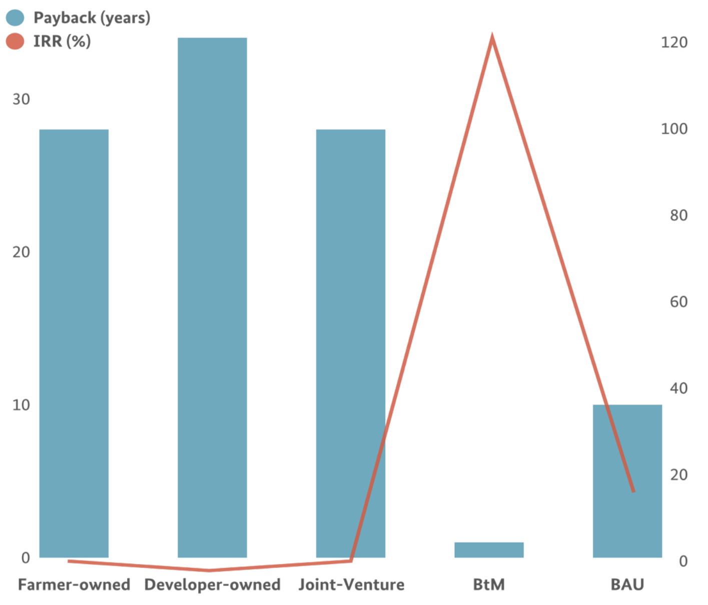
As mentioned in the above section 5.3-Maharashtra, the feed-in tariff considered for a solar PV project is INR 3.01 per kWh. The tariff was used in the business model to check financial results such as payback period and Internal rate of return (IRR).

For the business models, the analysis is carried out for 25 years with assumptions for the solar PV system and agriculture to determine the net revenue from each model. The assumptions are mentioned in detail in Annexure 10.4 for reference. The capital cost for the overhead solar PV system was gathered through research and discussion with key informants.

Using the prevalent solar feed-in tariff of INR 3.01 per kWh, the farmer-owned, developer-owned and joint-venture business model returned a payback of higher than 25 years with a negative IRR percentage, indicating that the financial feasibility of the proposed system is very poor. The Behind-the-Meter (BtM) model was found to have a payback period of one year, with an IRR of 120%, making it financially attractive. Since the model involves self-consumption of electricity generated by the solar PV system through net metering, compensated at the industrial tariff of INR 8.72 per kWh, the avoided cost of electricity from the grid results in higher savings compared to other models.

It was considered that for the system to be financially feasible, an IRR of 14% is required. In this case, under the prevalent solar feed-in tariff, all the business models, expect Behind-the-meter model (BtM), were considered to be financially infeasible. Further, this prompted the query of finding out the minimum feed-in tariff at which other business models would become financially feasible.

Figure 6: Payback period and Internal rate of return for all the business models at prevalent feed-in tariff

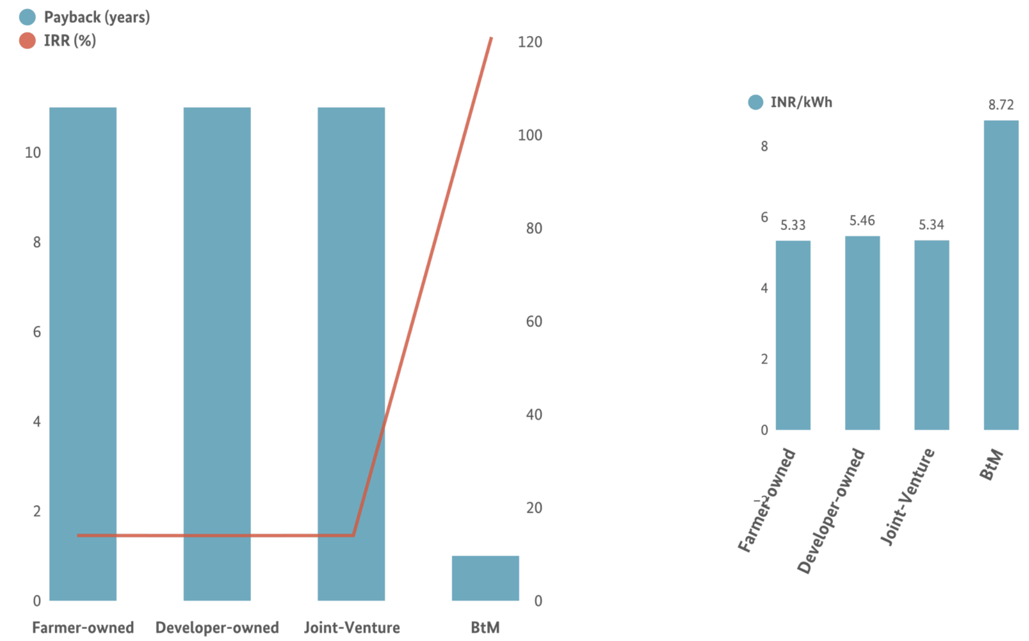


	Payback	IRR
Farmer-owned	28.00	-0.01%
Developer-owned	34.00	-2.20%
Joint-Venture	28.00	-0.01%
BtM	1.00	121.00%
BAU	10.00	15.88%

Minimum solar feed-in tariff

As discussed above, the business model now was programmed to achieve an IRR of 14% through a goal-seek program. This allowed us to identify the minimum solar feed-in tariff required to achieve financially attractive returns. The minimum solar feed-in tariff discovered for the business models is shown in figure 7 below with its respective payback period in years and IRR in percent.

Figure 7: Left: Payback period and IRR for respective business models Right: Minimum solar feed-in tariff in each business model



	Payback	IRR
Farmer-owned	11.00	14.01%
Developer-owned	11.00	13.99%
Joint-Venture	11.00	14.01%
BtM	1.00	121.00%

As seen from the above figure, the minimum solar feed-in tariff to achieve an IIR of 14% ranges from INR 5.34 to INR 5.46 per kWh depending on the business model. In the BtM case, where the FPO acts as a developer, the self-consumption of the generated solar energy, with net metering, can replace the imported grid energy under the industrial tariff of INR 8.72 per kWh, resulting in a higher IRR percent.

Farmer revenue share:

In this section, the farmer revenue streams are detailed for each of the selected business models. In the farmer-owned model, the farmer receives both the solar and the farming revenue streams, giving the farmer maximum revenue as compared to other models. In the developer-owned model, the farmer is responsible for agriculture but also earns added revenue in the form of land lease income paid by the solar developer for occupying the farmland. In the joint-venture model, the farmer brings in his land as equity into the solar business, resulting in the farmer earning revenue share from the solar PV system. The results in the below figure show a comparison of 25-year discounted net revenue for each of the business models.

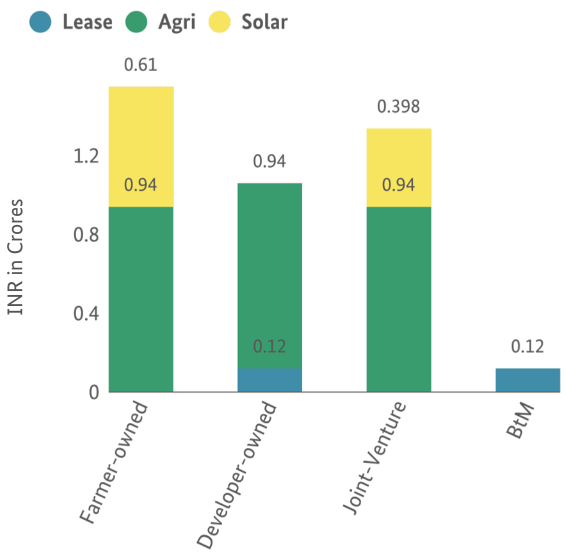


Figure 8: 25-year discounted farmer revenue stream for each of the selected business models

Sensitivity analysis – Internal rate of return (IRR)

A sensitivity analysis was conducted to evaluate the impact of varying capital costs and solar feed-in tariffs on the internal rate of return (IRR) of an AgriPV system. The capital cost adjustments accounted for differences in evacuation requirements (based on the distance to the point of interconnection) as well as structural and construction needs. The solar feed-in tariff was varied to assess its effect on the IRR. The analysis revealed that a positive IRR was achieved across all business models only when the feed-in tariff exceeded INR 4.50 per kWh. For the selected system, with a capital cost and a feed-in tariff of INR 5.34 per kWh, the payback period was found to be 11 years.

Table 7: IRR sensitivity analysis with varying capital cost assumptions at minimum feed-in tariff

	IRR by Capital cost variations			
BM-Model	3,08,53,218	3,21,61,500	3,87,95,400	4,16,74,285
Farmer-owned	15.43%	14.01%	8.48%	6.69%
Developer-owned	15.42%	13.99%	8.46%	6.67%
Joint Venture	15.43%	14.01%	8.48%	6.69%
BtM model	135.19%	120.97%	66.87%	51.16%

Sensitivity analysis – Distributed renewable energy certificate (D-REC)

A D-REC scheme is considered as an additional revenue to find the impact on the internal rate of return (IRR) for the selected business models. The analysis considers a D-REC disbursement for 10 years. The per unit D-REC credit allocated varied from INR 0.20 per kWh to INR 1.00 per kWh. D-REC and or carbon credits maybe a viable option to increase the financial viability of AgriPV.

Table 8: IRR sensitivity analysis with D-RECs

	D-REC credit – 10 year scheme (INR/kWh)					
BM-Model	0	0.20	0.40	0.60	0.80	1.00
Farmer-owned	14.01%	14.64%	15.26%	15.86%	16.44%	17.01%
Developer-owned	13.99%	14.66%	15.28%	15.89%	16.47%	17.03%
Joint Venture	14.01%	14.64%	15.26%	15.86%	16.44%	17.01%
BtM model	120.97%	121.03%	121.08%	121.14%	121.20%	121.26%

6.1.2. Conclusion

AgriPV systems in Maharashtra aimed at selling energy to distribution companies under the current solar feed-in tariffs are not viable, as the return on investment is insufficient. To achieve a desired IRR of 14%, the required solar feed-in tariff ranges from INR 5.34 to INR 5.46 per kWh—significantly higher than the current rate of INR 3.01 per kWh. This highlights the need for a higher solar feed-in tariff to make AgriPV systems financially viable and attract investment. The introduction of D-RECs can help increase net revenue, which would further incentivize investors and should be facilitated.

However, „Behind-the-meter“ AgriPV systems operating under net metering, supplying solar energy to food processing units, offer a potentially more financially attractive option. Additionally, selling solar energy through Open Access or Green Open Access channels may be promising, though in this case, AgriPV will compete with the lower power costs of ground-mounted solar energy systems.

6.2. AgriPV Business Models for Apple Farming

The key assumptions utilized for the business modelling of AgriPV for apple farming in Kullu and Shimla districts are provided below (table 9). For a complete listing of assumptions refer to Annexure 10.4. The assumptions utilized were informed by literature research, the key informant interviews with experts and data collected during field visits.

The average landholding of a farmer was assumed to be 1.50 acres. It was determined that an overhead AgriPV system of 0.31MW could be installed in the available area with the selected arrangement. While the AgriPV system configuration for apple farming is the same as the one modelled for potato farming in the earlier section a cost increase of 20% for the elevated structure was assumed owing to higher wind speeds in the region. In this case, it was assumed that the installation of overhead systems would not impact the productivity of the apple or lead to a reduction in farmable land. The primary reason for the assumption was that the selected configuration would provide sufficient sunlight for optimal growth and the spacing between the trees also facilitated the installation of the structure without compromising the available land for farming.

Table 9: Assumptions considered for business model – Apple

Assumption	Value
Solar PV system capacity	0.31 MW
Height of the system	5.00 m
Row distance between shed	9.50 m
Capital cost (AgriPV)	INR 1,67,09,000/-
Solar feed-in tariff	3.50 INR/kWh
Average productivity per acre (AgriPV)	12.50 MT
Net revenue per acre (AgriPV)	INR 4,37,500/-
Rent per acre	INR 2,50,000/-
Land value per acre	INR 75,00,000/-

6.2.1 Results and Observations

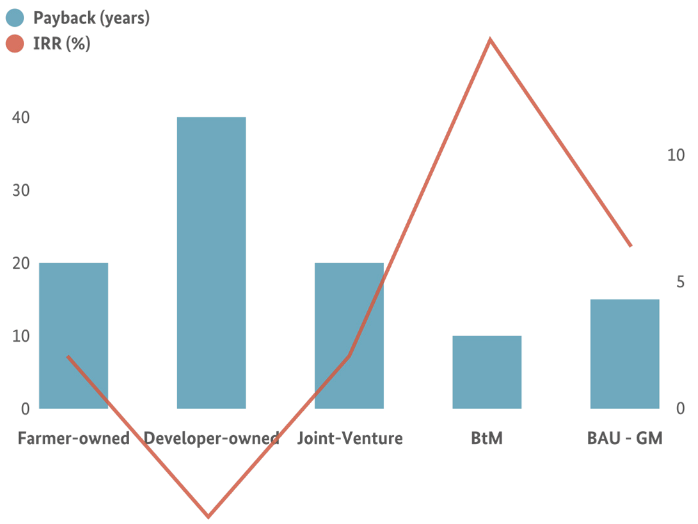
Prevalent feed-in tariff

As mentioned in Section 5.4 – Himachal Pradesh – energy sector profiling, the generic feed-in tariff for solar PV projects in Himachal Pradesh is INR 3.50 per kWh for solar PV projects up to 1 MW capacity. Hence, this is the feed-in tariff considered for business model simulation.

The business model analysis considers a period of 25 years and gives financial parameters such as payback period, Internal rate of return (IRR), 25-year discounted net revenue, and revenue streams for stakeholders are some of the outputs. The business-as-usual (BAU) case is assumed to have the same capacity of solar PV ground-mounted system. The capital cost considered for BAU case differs as compared to AgriPV particularly due to the structure costs (capital cost – 3.67 Crore/MW). The assumptions for the BAU case are shared in the Annexure 10.4.

The financial parameter of IRR was taken as a critical parameter for analysing the financial feasibility of the AgriPV system. An IRR of 14% is considered a financially attractive investment and can appeal to investors and other stakeholders.

Figure 9: Payback period and Internal rate of return for all the business models at prevalent feed-in tariff



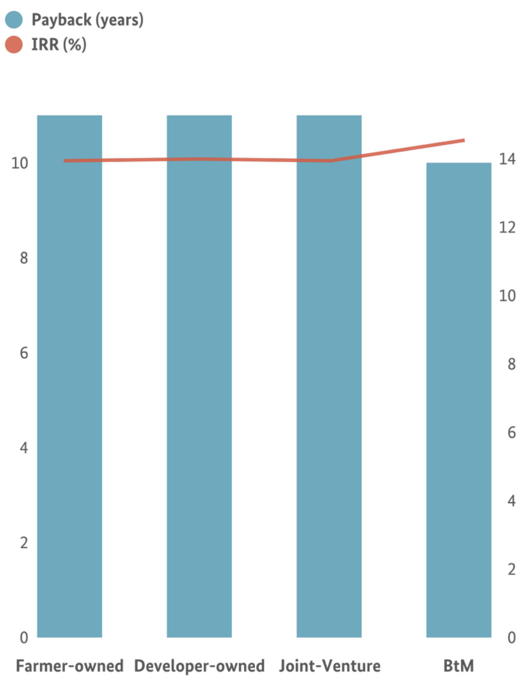
	Payback	IRR
Farmer-owned	20	2.06%
Developer-owned	40	-4.29%
Joint-Venture	20	2.06%
BtM	10	14.54%
BAU - GM	15	6.38%

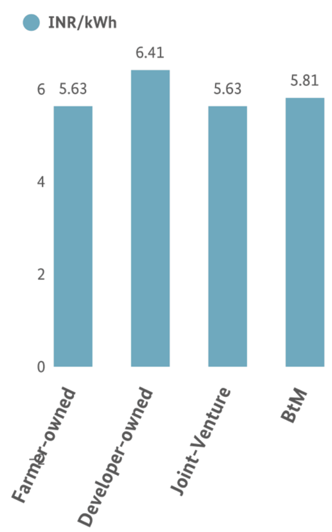
As seen from the above figure, the existing solar feed-in tariff for solar PV projects yields an undesirably high payback period in all the selected business models. The developer-owned model yielded a payback period of above 25 years and a negative IRR. A business-as-usual (BAU) case of ground-mounted (GM) solar PV system was simulated for comparison with the other models. However, the Behind-the-meter (BtM) model was the only case with an IRR of above 14.00%. In this model, the solar energy generated is self-consumed under net metering mechanism replacing the industrial grid tariff of INR 5.81 per kWh. From the above analysis, it is clear that the existing prevalent feed-in tariff would not attract stakeholders and investors owing to the low financial feasibility of the selected models. However, it would be beneficial to determine the minimum feed-in tariff for achieving the desired IRR of 14% to further revisit and revise the feed-in tariff for AgriPV projects.

Minimum Solar Feed-in Tariff:

To determine the financial feasibility of the selected business models the financial parameters were noted for achieving an IRR of 14%. A goal-seek program was executed to find out the minimum solar feed-in tariff required for an IRR of 14%. The minimum solar feed-in tariff to achieve the desired IRR is shown in the figure below.

Figure 10 Left: Payback period and IRR for respective business models; Right: Minimum solar feed-in tariff in each business model





As seen from the above figure, the minimum solar feed-in tariff ranges from INR 5.63 to INR 6.41 per kWh for the selected business models.

	Payback	IRR
Farmer-owned	11.00	13.94%
Developer-owned	11.00	13.99%
Joint-Venture	11.00	13.94%
BtM	10.00	14.54%

In Himachal Pradesh, the tariff for industrial consumers with a high-tension connection is INR 5.81 per kWh. In the BtM model, the generated electricity is self-consumed through the net metering mechanism, resulting in higher savings by avoiding electricity costs. These savings lead to an IRR of over 14%, indicating that the model is financially attractive. This informs us that in case a net metering mechanism is adopted for the accounting of the use of generated electricity, the current industrial tariff can result in a financially attractive investment resulting in an IRR above 14%.

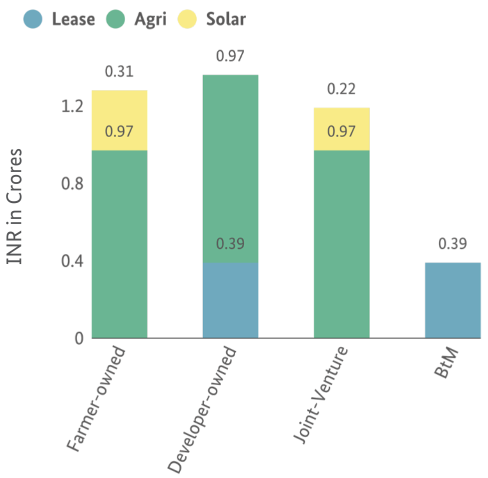
Farmer revenue share

The 25-year discounted net revenue from each of the business models is calculated to identify the various revenue streams for the farmer in each business model. The developer-owned model offers the highest 25-year discounted net revenue, owing to the additional revenue to the farmer in the form of rent paid for the land occupied by the developer. However, in this model, the developer would have a need for a high feed-in tariff of INR 6.41 per kWh to achieve the desired IRR. Additionally, in the BtM model, the farmer earns revenue only from the rent/lease amount paid by developer (in this case FPO/FPC) for occupying the land.

Unlike in the potato example for apple farming no reduction in the crop yield is assumed, the revenue for the farmer from selling his produce remained the same in all the selected business models.

The various revenue streams for the farmer in each business model can be identified from the figure below. The additional revenue from rent/lease in a developer-owned model allows the farmer to attain a stable revenue source. The additional revenue from the share of electricity sold in the farmer-owned as well as joint-venture models facilitates an additional income for the farmer.

Figure 11: 25-year discounted farmer revenue stream for each of the selected business models



Sensitivity analysis – Internal rate of return (IRR)

A sensitivity analysis was conducted to evaluate the impact of varying capital costs and feed-in tariffs on the internal rate of return (IRR) of an AgriPV system. The capital cost adjustments accounted for differences in evacuation requirements (based on the distance to the point of interconnection) as well as structural and construction needs.

The feed-in tariff was varied to assess its effect on the IRR. The analysis revealed that a positive IRR was achieved across all business models only when the feed-in tariff exceeded INR 5.00 per kWh. For the selected system, with a capital cost and a feed-in tariff of INR 5.63 per kWh, the payback period was found to be 11 years.

Table 10: IRR sensitivity analysis with varying capital cost assumptions

	IRR by Capital cost variations			
BM-Model	INR 1,60,29,303	INR 1,67,09,000	INR 2,01,55,538	INR 2,16,51,217
Farmer-owned	15.37%	13.95%	8.44%	6.66%
Developer-owned	15.59%	14.02%	8.39%	6.67%
Joint Venture	15.37%	13.95%	8.44%	6.66%
BtM model	16.44%	14.54%	7.42%	5.17%

Sensitivity analysis – Distributed renewable energy certificate (D-REC)

A D-REC scheme is evaluated as an additional revenue stream to assess its impact on the internal rate of return (IRR) for the selected business models. The analysis assumes D-REC disbursements over a 10-year period, with per-unit D-REC credits ranging from INR 0.20 to INR 1.00 per kWh. Incorporating D-RECs and/or carbon credits could be a viable approach to enhancing the financial viability of AgriPV systems.

Table 11: IRR sensitivity analysis with D-RECs

	D-REC credit – 10 year scheme (INR/kWh)					
BM-Model	0	0.20	0.40	0.60	0.80	1.00
Farmer-owned	13.94%	14.55%	15.14%	15.72%	16.27%	16.81%
Developer-owned	13.99%	14.61%	15.20%	15.78%	16.34%	16.89%
Joint Venture	13.94%	14.55%	15.14%	15.72%	16.27%	16.81%
BtM model	14.54%	15.38%	16.18%	16.95%	17.69%	18.40%

6.2.2. Conclusion

The business model analysis in the case for apple farming in Himachal Pradesh showed that there is an opportunity for the farmers to earn additional revenue as compared to BAU case. However, the financial feasibility of the AgriPV system is highly influenced by the solar feed-in tariff and the capital cost considered in the analysis. The minimum feed-in tariff to achieve a desired IRR of 14% ranged between INR 5.63 to INR 6.41 per kWh, which is considerably higher than the current compensation rate of INR 3.50 per kWh. This indicates the need for a higher solar feed-in tariff for the AgriPV system to be financially viable and to attract investments.

Additional revenue streams such as D-REC can help in increasing the net revenue and must be facilitated to further attract investors.

Multidimensional Feasibility

7.

Assessing AgriPV deployment in India reveals mixed expert insights on technological, regulatory, cultural, ecological, and economic feasibility, highlighting both challenges and opportunities for sustainable agricultural innovation.

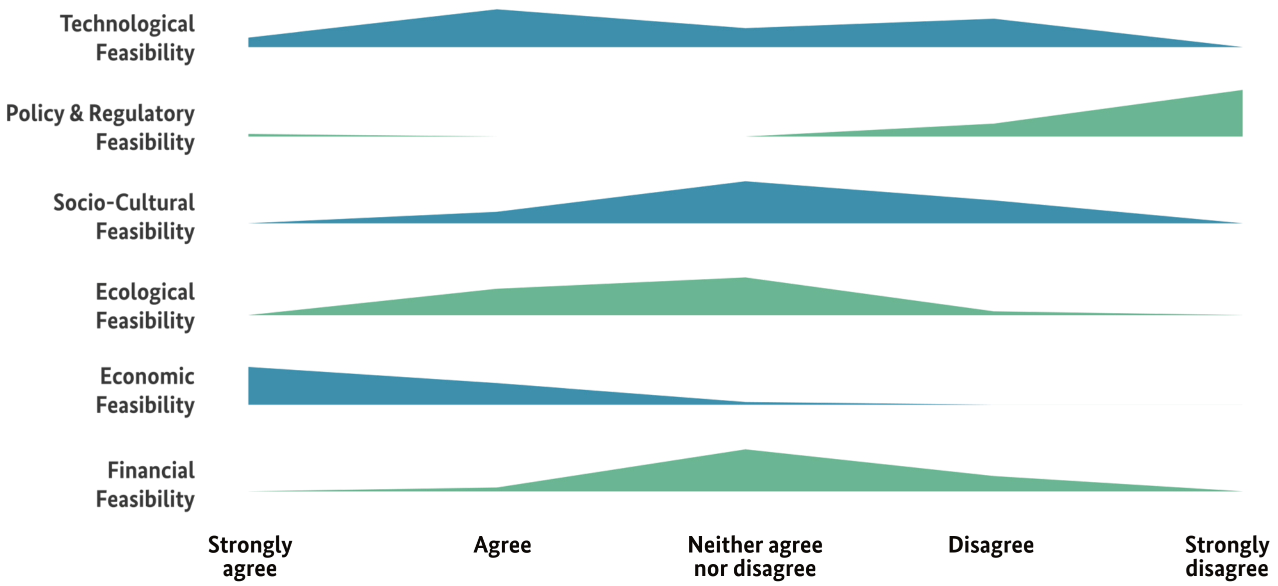
This section conducts a multidimensional feasibility assessment of AgriPV deployment in India based on expert insights. The assessment covers the following key dimensions:

- Technological Feasibility
- Policy and Regulatory Feasibility
- Socio-Cultural Feasibility
- Ecological Feasibility
- Economic Feasibility
- Financial Feasibility

A detailed explanation of each dimension can be found in Annexure 10.1 the polling tool is available in Annexure 10.2.

A poll was conducted in the AgriPV India WhatsApp Group, an informal network of experts from agriculture, energy, water, and other related sectors. The group consists of over 100 members. Six poll questions were shared over 10 days from the 24th of September to the 3rd of October 2024, with an average response rate of 20%. The poll results are shown in the figure below.

Figure 12: Multidimensional feasibility poll result



Experts are divided on the technological feasibility of AgriPV, highlighting key challenges such as access to agricultural land, inadequate power evacuation infrastructure, and limited research on crop selection. There is a consensus that significant improvements in the policy and regulatory framework are necessary to promote AgriPV in India. Specifically, attention must be given to farmer protection, land-use regulations, and the integration of AgriPV with other policy priorities and sectors. Regarding cultural feasibility and farmers' perceptions of AgriPV, most expert opinions were neutral, indicating low awareness of AgriPV within the farming community. However, GIZ India recently conducted workshops for 1,700 farmers, revealing that 54% expressed interest in installing an AgriPV system. Experts' opinions on the ecological feasibility and benefits of AgriPV tend to be cautiously positive. They noted that while fencing around AgriPV systems could negatively impact animal movement, it is necessary to secure an insurance policy. There was a clear positive trend among experts regarding the broader economic benefits of AgriPV. However, they expressed caution about its financial viability in India today, suggesting that AgriPV is not yet a financially viable proposition.

CONCLUSIONS AND RECOMMENDATIONS

8.

The feasibility analysis of AgriPV integration for apple farming in Himachal Pradesh and for Potato farming in Maharashtra highlights several key insights and actionable recommendations for its implementation, particularly, where unique agricultural conditions and fragmented landholdings and sensitive environments present both challenges and opportunities.

Absence of environmental standards and an environmental and social impact assessment mandate (ESIA): Currently, there is no mandatory requirements for AgriPV or for solar systems to undertake an ESIA and to mitigate ecosystem services impact from its deployment. The absence of a mandatory ESIA indicates an area where regulatory attention may be warranted to safeguard ecosystems. The environmental impacts of AgriPV may vary according to the size of the installation, with smaller AgriPV systems possibly resulting in lesser ecosystem and land-use impacts than larger ones, highlighting the need for careful site selection and land-use guidelines.

Recommendation: Instituting mandatory impact ESIA before AgriPV installations would help evaluate and mitigate any adverse effects on crop yields and ecosystems. Land-use and zoning regulations could limit the permissible AgriPV capacities, particular so in highly ecologically sensitive areas.

Importance of crop selection to mitigate crop yield reduction: The adoption of AgriPV systems could potentially reduce yields for certain crops, a crop yield reduction for example is expected for potatoes, this highlights a need for strategic crop selection.

Recommendation: To mitigate possible yield reductions, further research should focus on specific crop types to understand how AgriPV impacts yields and develop guidelines that aid farmers in choosing crops compatible with AgriPV systems

Behind-the-meter (BtM) AgriPV systems as early adopters: The results of the business model analysis that indicates that BtM AgriPV systems are currently the only financially viable deployment options of AgriPV. Future electrification of farm machinery, including tractors and other currently fossil-fuel-dependent equipment, could make BtM AgriPV attractive to farmers.

Recommendation: Educational initiatives, such as workshops, are recommended to help Farmer Producers Companies, Food Processing Units, farmers and other stakeholders grasp the benefits of the ‚Behind-the-Meter' model and its operational requirements. Additionally, the potential for farm equipment electrification for apple and potato farmers need to be assessed.

Grid interconnection standards pose significant limitations for smallholder farmers in AgriPV participation: The average landholding size in Himachal Pradesh and Maharashtra (3.36 acer per holding in Pune district, 1.97 acres in Kullu district and 1.28 acres in Shimla district) and allows AgriPV systems with power capacities only between 300 to 600 kW. Additionally, landholdings in Himachal Pradesh are highly fragmented, with individual farmers' lands often spread across multiple parcels. Many states mandate a minimum solar power capacity of 500 kW or more for grid interconnection to enable electricity sales. This requirement restricts smallholder farmers from effectively participating in AgriPV.

Recommendation: Promote grid-interconnection standards that permit the participation of small AgriPV systems in the energy markets.

Capital investment is deterring: Farmers face challenges in affording the initial investment for AgriPV systems, though Farmer Producer Organisations (FPOs) show strong interest in investing and developing these systems, seeing value in their potential to enhance local agricultural sustainability.

Recommendation: To address farmers' financial constraints, funding options low-interest loans and project-based financing could alleviate the initial investment burden, making AgriPV more accessible for farmers. However, this will require in the first place solar feed-in tariffs that allow an attractive return on investment.

Incumbent low solar feed-in tariffs and the higher capital cost make AgriPV a non-starter:
The low solar feed-in tariffs for sale of electricity to the public distribution companies makes AgriPV with its higher upfront costs, compared to conventional ground-mounted solar PV, a non-starter. While there is the possibility of AgriPV system availing the Open Access or Green Open Access Route for the sale of electricity it is unlikely that it will find many takers as it still will have to compete with solar PV systems that deliver electricity at a lower cost.

Recommendation: If AgriPV is a policy priority, then additional; opportunities to monetize some of its environmental and energy benefits need to be explored. This may include Distributed Renewable Energy Credits, Carbon Credits and locational solar feed-in tariffs that acknowledge the upstream grid benefits of distributed renewable energy sources (reduced distribution and transmission losses, transmission and distribution capacity benefits etc.).

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10 Annexure

10.1 Definition of feasibility dimensions

Technological Feasibility

Technological Feasibility assesses whether a technology like AgriPV can be successfully implemented and scaled based purely on technical aspects and resource availability. Key factors include:
Maturity of the Technology: Evaluates the readiness of AgriPV, including solar panel efficiency and integration with agriculture.
Supply Chain Availability: Considers the availability of essential components for large-scale deployment.
Infrastructure Compatibility: Examines the ability of the electrical grid to support AgriPV.
Resource Requirements: Evaluates sunlight availability and land suitability.
Scalability: Assesses whether the technology can expand without issues.
Technical Workforce: Ensures sufficient skilled labour is available.

This analysis excludes economic or institutional barriers, focusing on the technical potential for large-scale AgriPV deployment in India.

10.1.1. Policy and Regulatory Feasibility

Policy and regulatory feasibility for AgriPV (Agrivoltaics) in India focuses on the frameworks that promote the integration of solar energy in agriculture. Key elements include national and state government initiatives that offer financial incentives like subsidies and low-interest loans and favourable policies for selling excess energy back to the grid. Zoning laws support dual land use for farming and solar generation, while environmental regulations ensure sustainability. Enhanced grid connectivity and infrastructure investment are vital for successful implementation. Additionally, training programs help educate farmers about AgriPV benefits, and consistent policies foster long-term investment. Together, these elements create a supportive environment for the large-scale deployment of AgriPV, promoting sustainable development and energy independence.

10.1.2. Socio-Cultural Feasibility

The pace of transformation toward AgriPV (Agrivoltaics) is significantly influenced not only by institutional factors but also by the attitudes and behaviours of farmers. Their perceptions of AgriPV can play a crucial role in determining its adoption; for instance, if farmers view these systems as beneficial for increasing crop yields and providing additional income through energy sales, they are more likely to embrace the technology. Conversely, scepticism about the effectiveness, concerns about the initial costs, or fears regarding potential disruptions to traditional farming practices can impede adoption. Understanding and addressing these perceptions through targeted education, demonstration projects, and community engagement can help mitigate resistance and foster a more supportive environment for the integration of solar energy in agriculture, ultimately facilitating a smoother transition to sustainable practices.

10.1.3. Ecological Feasibility

Ecological feasibility assesses the environmental sustainability of AgriPV by examining how these solar energy systems interact with and impact local ecosystems. This includes evaluating the potential effects on biodiversity, as AgriPV should ideally promote rather than harm local flora and fauna. The design and implementation of AgriPV projects must consider factors such as soil health, water usage, and habitat preservation to ensure that agricultural productivity is enhanced alongside energy generation. Additionally, by integrating solar panels with crops, AgriPV can provide benefits like improved micro-climates and reduced soil erosion, ultimately supporting ecosystem services such as pollination and carbon sequestration. A careful approach that prioritizes ecological integrity not only aids in the successful adoption of AgriPV but also contributes to the overall resilience of agricultural landscapes in the face of climate change.

10.1.4. Economic feasibility

Economic feasibility examines the broader economic implications of adopting AgriPV (Agrivoltaics) by analyzing its potential benefits and challenges across regional, national, and global contexts. This assessment includes evaluating how AgriPV can drive job creation, particularly in sectors related to renewable energy installation, maintenance, and agricultural innovation, thereby enhancing local employment opportunities. It also considers income distribution effects, as integrating solar energy may increase farmers' revenues through energy sales, while potentially diversifying income streams and reducing reliance on traditional agricultural practices. Furthermore, the deployment of AgriPV can stimulate market growth by fostering new industries and technologies, contributing to economic resilience by reducing vulnerability to fluctuating energy prices and climate impacts. Overall, understanding these economic dimensions is crucial for policymakers and stakeholders to ensure that AgriPV adoption leads to sustainable economic development and enhanced community well-being.

10.1.5. Financial feasibility

Financial feasibility for AgriPV (Agrivoltaics) involves assessing the economic viability of integrating solar energy systems into agriculture by analysing initial and operational costs, potential revenue from energy production and enhanced crop yields, and additional income opportunities. It considers long-term benefits such as cost savings from reduced energy expenses and environmental impacts, alongside risks from market fluctuations and regulatory changes. Key metrics like payback period, NPV, and IRR help evaluate profitability, while financing options such as grants and loans provide support. Comprehensive feasibility studies tailored to local conditions are essential for informed decision-making by farmers and investors regarding solar integration in agriculture.

10.2. Multidimensional polling tool

Technological Feasibility
AgriPV technology is ready for large-scale deployment in India, considering only its technical capabilities, resource availability, and infrastructure compatibility.
Strongly agree – agree – neither agree nor disagree – disagree, strongly disagree

Policy and Regulatory Feasibility
Current and state-level policies and regulations facilitate the large-scale deployment of AgriPV in India.
Strongly agree – agree – neither agree nor disagree – disagree, strongly disagree

Socio-Cultural Feasibility
Third question Farmers‘ current perceptions of AgriPV support its widespread adoption.
Strongly agree – agree – neither agree nor disagree – disagree, strongly disagree

Ecological Feasibility
AgriPV systems are compatible with the local ecosystems and can enhance biodiversity.
Strongly agree – agree – neither agree nor disagree – disagree, strongly disagree

Economic Feasibility
AgriPV adoption and deployment will create economic benefits at local, state and national levels. This includes its effects on job creation, income distribution, market growth, and economic resilience.
Strongly agree – agree – neither agree nor disagree – disagree, strongly disagree

Financial Feasibility
AgriPV is financially viable for all key stakeholders, including developers and farmers, considering factors such as upfront costs, potential revenue from energy production, crop yields, and land lease.
Strongly agree – agree – neither agree nor disagree – disagree, strongly disagree

10.3 Arrangement of overhead solar PV system

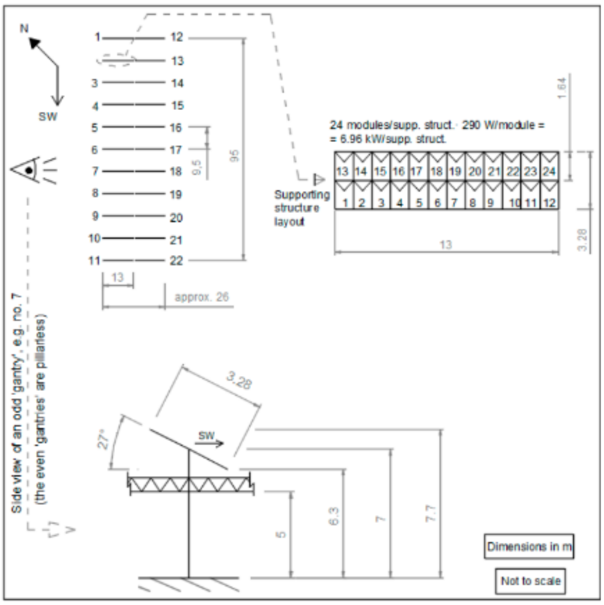
The overhead system was proposed as a potential solution for solar PV installation on the available farmland. The primary objective of selecting this system was to maximize solar PV generation while ensuring adequate sunlight for the chosen crops.

The structure of the overhead system was designed to be elevated to a height of 5 meters. This height was determined based on existing research and data gathered from site visits. The structure would support 10 solar PV panels arranged lengthwise, spanning a distance of 13 meters (with each solar PV panel assumed to be 1.20 meters in length). The arrangement would vary for different crops—potatoes and apples—since their sunlight requirements differ. The system was designed to accommodate 10 solar PV panels for potatoes and 20 solar PV panels for apples, placed along the width of the structure. For apples, the width of the structure was determined to be 4.60 meters (2 panels × 2.30 meters), while for potatoes, it was 2.30 meters.

The structure housing 10 solar PV panels for potato cultivation and 20 solar PV panels for apple farming will be referred to as a „shed“ in this document. These sheds would be positioned in rows adjacent to each other. The spacing between rows would differ—5 meters for potatoes and 9.5 meters for apples—to allow for optimal sunlight exposure for each crop.

The design of each system was informed by prior research and studies specific to the selected crops. The following figure illustrates the proposed arrangement of the solar PV panels within the shed.

Figure 13: Proposed arrangement of solar PV panels in a shed housing 24 panels



10.4 Assumptions for business model

Table 12: General assumptions for AgriPV business models

GENERAL ASSUMPTIONS	VALUE	UNIT
Agriculture is already happening in the area		
Inverter sizing assumed the same as PV size		
Elevated system to 5 metres	5.00	m
Capacity Utilisation factor (CUF)	19.00	%
Agricultural revenue increase	4.00	%
PV lifetime is considered as 25 years	25.00	years
Net revenue from agriculture is also considered for 25 years	25.00	years
O&M expenses for first year (% of capital cost)	1.40	%
O&M expenses increases year on year	5.72	%
Debt:Equity ratio	30:70	
Loan term	10	years
Loan interest	9.00	%
Moratorium	1	year
Discount rate is assumed to be 8.67%	8.67	%
Working capital for spares is assumed to be 15% of the annual O&M	15.00	%
Interest on working capital is assumed to be 11%	11.00	%
Assumptions specific to BM-1	Value	Unit
No land purchase cost		
Farmer is the developer		
No land lease or rent assumed		

Table 13: Assumptions specific for each business models

ASSUMPTIONS	FARMER-OWNED	DEVELOPER-OWNED	JOINT-VENTURE	BEHIND-THE-METER
Land cost – HP/MH -INR per acre	NA	NA	75,00,000/ 50,00,000	NA
Solar PV responsibility	Farmer	Developer	Involved parties	FPO/FPC
Agriculture responsibility	Farmer	Farmer	Involved parties	FPO/FPC
Land rent/lease HP/MH – INR per acre	NA	2,50,000/ 60,000	NA	2,50,000/ 60,000
Industrial category tariff - Maharashtra – HT (INR/kWh)	NA	NA	NA	8.72
Industrial category tariff - Himachal Pradesh – HT (INR/kWh)	NA	NA	NA	5.81

Table 14 Assumptions for ground mounted solar PV

BAU - GROUND MOUNTED	VALUE	UNIT
BAU – Capital cost – HP (0.31 MW)	**1,14,00,250/**	**INR**
BAU – Capital cost –MH (0.6 MW)	**1,89,00,000/-**	**INR**

10.5 Site visit brief

Key findings

	Pune	Kullu	Delhi (existing AgriPV)
Awareness	Farmers were unaware of AgriPV systems initially but became more interested after learning about different business models.	Farmers were unaware about the AgriPV system. The main concern was receiving adequate sunlight for the crops.	Farmers in the area are aware of the AgriPV concept but are cautious.
Productivity	Potato productivity ranges from 8-10 metric tons per acre in Kharif season to 12-14 metric tons in Rabi season. Water-saving practices like sprinkler irrigation have reduced water-related crop damage.	Traditional apple variety produces around 80-120 kg of apples. Transitioning to dwarf apple varieties (M9) to increase productivity is popular.	There is a 30% drop in productivity under the solar panels, particularly in crops like potatoes. Other crops like turmeric, vegetables, and fruit trees still perform well.
Land Value	Agricultural land is valued at INR 60 lakh per acre in plains and INR 40 lakh per acre in mountainous areas	Land values in Kullu vary from INR 15-20 lakh per bigha (1/5th acre) near roads to INR 5-7 lakh in the mountains.	Not specifically mentioned, but the system generates rent and income for the farmer managing the AgriPV operations.
Business Model	Farmers showed interest in exploring business models but were sceptical.	The potential for joint ventures between farmers and developers was discussed, but upfront investment concerns were raised.	A RESCO model is used, where electricity generated is sold to hospitals, and the farmer receives rent and a salary.
Cost	Farming input and operation costs are around INR 1,00,000 per acre, with net revenues depending on market prices.	The cost of apple production is INR 20-25/kg, with total costs rising to INR 35-40/kg, influenced by labour and other expenses.	Monthly operational costs are INR 1,50,000 for farm and PV system maintenance. Additional INR 50,000 is spent for sourcing RO water.
Mechanization	Mechanization is moderate, mainly through sprinkler systems, tractors and solar water pumps.	Limited mechanization due to the mountainous terrain, though sprayers and sorting machines are used.	Tractors and farm machinery can pass under the solar panels, supporting mechanization. Drip irrigation has significantly reduced water demand.
Role of Women	Women (30 in Bhama-Bhima, 70 in Saathgaon) are involved but mainly in labour roles; however, their decision-making influence is increasing.	Women have increasing involvement in farm management, though they remain traditionally more involved in labour.	No specific mention, but the farmer has employees, including women, involved in various tasks.
Biodiversity	Decline in birds and insects due to industrialization and pesticide use.	Concerns about a decline in biodiversity due to climate change, pesticide use, and new pests/fungi.	The AgriPV system has improved local biodiversity by providing shelter for birds and attracting pollinators.

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