INTERNATIONAL SOLAR ALLIANCE

GLOBAL AGRIPHOTOVOLTAICS

CLIMATE-ZONE TECHNICAL FRAMEWORK

Symbiotic design considerations for agriphotovoltaic (AgriPV) systems in ISA member countries across five climatic zones



October 2026



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Acknowledgement

The Global Agriphotovoltaics Climate-Zone Technical Framework was prepared by the International Solar Alliance (ISA) under the overall guidance and leadership of Ashish Khanna, Director General, ISA.

ISA TEAM

Lead Authors

Jaymin Gajjar, Programme Senior Analyst, Knowledge Management and Institutional Development, and **Awadhesh Jha**, Chief of Unit, Programmes, Projects and Implementation Coordination.

Internal Technical Review

Sharath Chandra Rao, Distributed Solar Specialist – Rooftop, Agriculture and Pumpset, ISA. **Dr D. K. Singh** served as Technical Advisor to the study, providing technical guidance throughout its development.

Peer-Review Coordination

Kumar Vaibhav, Global Solar Fellow, ISA, coordinated the external expert peer-review process, consolidated reviewers' comments and facilitated the incorporation of feedback into the final report.

EXTERNAL PEER REVIEW

ISA extends its sincere appreciation to the external reviewers for their rigorous assessment, technical insights and constructive recommendations, which helped strengthen the analysis and conclusions of this report. Valuable review and feedback were provided by:

Dr Nikhil Gakkhar (Ministry of New and Renewable Energy, Government of India); **Dr Arun K. Tripathi** (The Energy and Resources Institute, TERI); **Dr Ashok Gulati** (Indian Council for Research on International Economic Relations, ICRIER); **Subhodeep Basu** (ICRIER); Bidisha Banerjee (ICRIER); **Bharath Jairaj** (World Resources Institute India, WRI India); **Tirthankar Mandal** (WRI India); **Lanvin Concessao** (WRI India); **Arundhita Bhanjdeo** (WRI India); **Hemakshi Malik** (WRI India); **Dr Max Trommsdorff** (University of Freiburg and Fraunhofer Institute for Solar Energy Systems ISE); **Soumya Garnaik** (Global Green Growth Institute); **Ashok Kumar Thanikonda** (Global Green Growth Institute); **Zorica Crisolli** (Deutsche Gesellschaft für Internationale Zusammenarbeit, GIZ); **Abhishek Shastri** (GIZ); **Shubhashree Chakraborty** (National Solar Energy Federation of India, NSEFI); **Phoebe O'Hara** (Energy Transitions Commission); **Cristina Cornaro** (University of Rome Tor Vergata); **Dr Aritra Ghosh** (University of Exeter); **Gulabsing Girase** (Gro Solar Energy); **Balaji Lakshmikanth** (Renkube); and **Vivek Saraf** (SunSeed APV).

TECHNICAL CONSULTANT

PricewaterhouseCoopers Private Limited (PwC India), led by **Vaibhav Singh**, Executive Director, and **Himanshu Arora**, Director, with **Nirvanjyoti Bhattacharjee**, Director; **Abhijit Kumar**, Associate Director; **Avantika Sharma**, Manager; **Sachin Zachariah**, **Ali Khattab**, **Arkdeep Chakraborty** and **Sravani Kundur**, Senior Associates; **Saptangshu Ghosh** and **Aditi Aishwarya**, Associates; and SAEV Private Limited, represented by **Surinder Ahuja**, CEO, and **Dr Shivi Jindal**, Vice President of Projects, provided research support and technical inputs across the five climatic zones.

REPORT DESIGN AND PRODUCTION

ISA acknowledges the PwC India team for its support in the design, layout and production of this report, including the presentation of technical content and visual elements.

CONTRIBUTORS

ISA expresses its sincere gratitude to the practitioners, researchers, project developers and institutions who contributed their time, data and field experience through stakeholder consultations, technical exchanges and site visits. ISA also acknowledges the operators of the agriphotovoltaic installations documented in the case studies and worked demonstrations.

Foreword



Ashish Khanna
Director General, International Solar Alliance

Solar power has become the backbone of the global energy transition, and with that success has come a constraint that was easy to overlook when capacity was small. Solar plants need land, and in much of the world the land with the best solar resource is also the land that grows food. For the members of the International Solar Alliance, many of which lie in the arid, semi-arid and tropical belts where both pressures are most acute, the question of how to add gigawatts without subtracting hectares of farmland is no longer theoretical.

Agriphotovoltaics offers a credible answer. Global installed capacity has grown from around 5 MWp in 2012 to more than 18 GWp in 2025, with operating plants on four continents and commercial markets in Japan, France, Germany, Italy and China. The technology has passed the point of proof. What has been missing is a common method, grounded in evidence and differentiated by climate, that allows a government, a developer or a financier to judge whether a given project will work for the field as well as for the grid. This Global Agriphotovoltaics Climate-Zone Technical Framework is ISA's contribution to closing that gap.

The Framework rests on a single proposition: agriculture must be the primary design driver. The conventional approach optimises the solar plant and treats whatever grows beneath it as incidental. The Framework reverses that sequence. The strategic agricultural objective for the climate zone is fixed first, crop selection then sets the light budget, and mounting height, row spacing and panel density follow from it. Energy yield, cost and constructability are optimised within the boundaries agriculture has set. This inversion is what separates genuine agriphotovoltaics from a ground-mounted plant with token cultivation, and it should be the test that programme eligibility and project approval apply. The evidence assembled here shows why climate must shape that test. Across the five Köppen–Geiger zones assessed, the same canopy of panels solves different problems: water conservation in dry regions, where field studies report savings of 15 to 30 per cent; protection from heat and intense rainfall in the tropics; crop quality and shelter from hail and frost in temperate farmland; season extension in continental climates. The outcome of shade is a product of design rather than a property of the technology, and the same crop can gain or lose under an array depending on layout, irrigation regime and soil. Agronomic claims must therefore rest on site-specific analysis and field monitoring, not on generic assumptions about the benefits of shade.

The Framework also sets out the benchmark by which dual use should be judged. Because panels are spaced for crops, agrivoltaic plants generate less electricity per hectare than conventional solar. That sacrifice is justified only where the combined output exceeds what the land would produce under separate uses, a Land Equivalent Ratio above 1.0; documented values range from 1.2 to 1.65. Regulators would do well to adopt the LER, paired with a minimum agricultural output threshold, as the condition for incentives. Electricity carries the project's bankability, while agricultural revenue sustains the legitimacy of the land use and the farmer's income. Who captures that value depends on ownership, and making farmer- and cooperative-owned models bankable will require blended finance, aggregation and standardised revenue-sharing.



The countries that have scaled agriphotovoltaics share four conditions: regulatory clarity on dual land use, targeted incentives, alignment of energy and agricultural strategy, and an ecosystem of research, standards and capacity building. None is beyond the reach of any ISA member. For many, the practical near-term route lies off the transmission grid altogether: distributed and behind-the-meter agriphotovoltaics that power irrigation pumps, cold storage, dairies and agro-processing, replacing diesel, placing value directly on the farm and sidestepping the interconnection constraints that slow utility-scale projects in much of the world.

One lesson from the markets that have moved first deserves particular emphasis. Agriphotovoltaics does not scale on the strength of small demonstration plots. A fraction of a hectare cannot test machinery access, grid behaviour, maintenance economics or the ownership arrangements that decide who benefits, and it generates no evidence that a lender or a ministry can act on. The pilots that matter are built at commercial scale, on real farms, under real tariffs, with agronomic and financial monitoring designed in from the outset. They are the mechanism through which a country's design standards, eligibility rules and financing instruments are tested and corrected before a national programme is launched. ISA will therefore direct its support towards pilots of this kind, and I would encourage member countries to think in megawatts and hundreds of hectares rather than in kilowatts. This Framework gives member countries a shared method for taking those steps. I am grateful to the technical team, our partners and the distinguished experts whose review strengthened every chapter. ISA will accompany its members in putting the Framework to work, through capacity building, knowledge exchange and support for the large-scale pilots that will turn indicative benefits into measured evidence. The transition we are building must be one in which the farmer, the field and the grid all gain.



Foreword



Shri Pralhad Joshi
President, International Solar Alliance
Union Minister of New and Renewable Energy, Government of India

One of the defining challenges of our time is to expand clean energy without compromising the land that feeds us. As countries pursue energy security and economic growth, competing demands for food, electricity and land are intensifying. Agrivoltaics offers a way forward, allowing agriculture and solar power to coexist on the same land. This is quite relevant for countries across the Global South, where growing energy needs, agricultural livelihoods and climate vulnerability often intersect.

In India, we recognise the deep connection between land, livelihoods and prosperity. Agrivoltaics builds on this relationship by enabling crops to grow beneath and between solar panels while generating clean electricity above. With thoughtful design, it can also help moderate heat stress, improve water-use efficiency and provide farmers with an additional source of income.

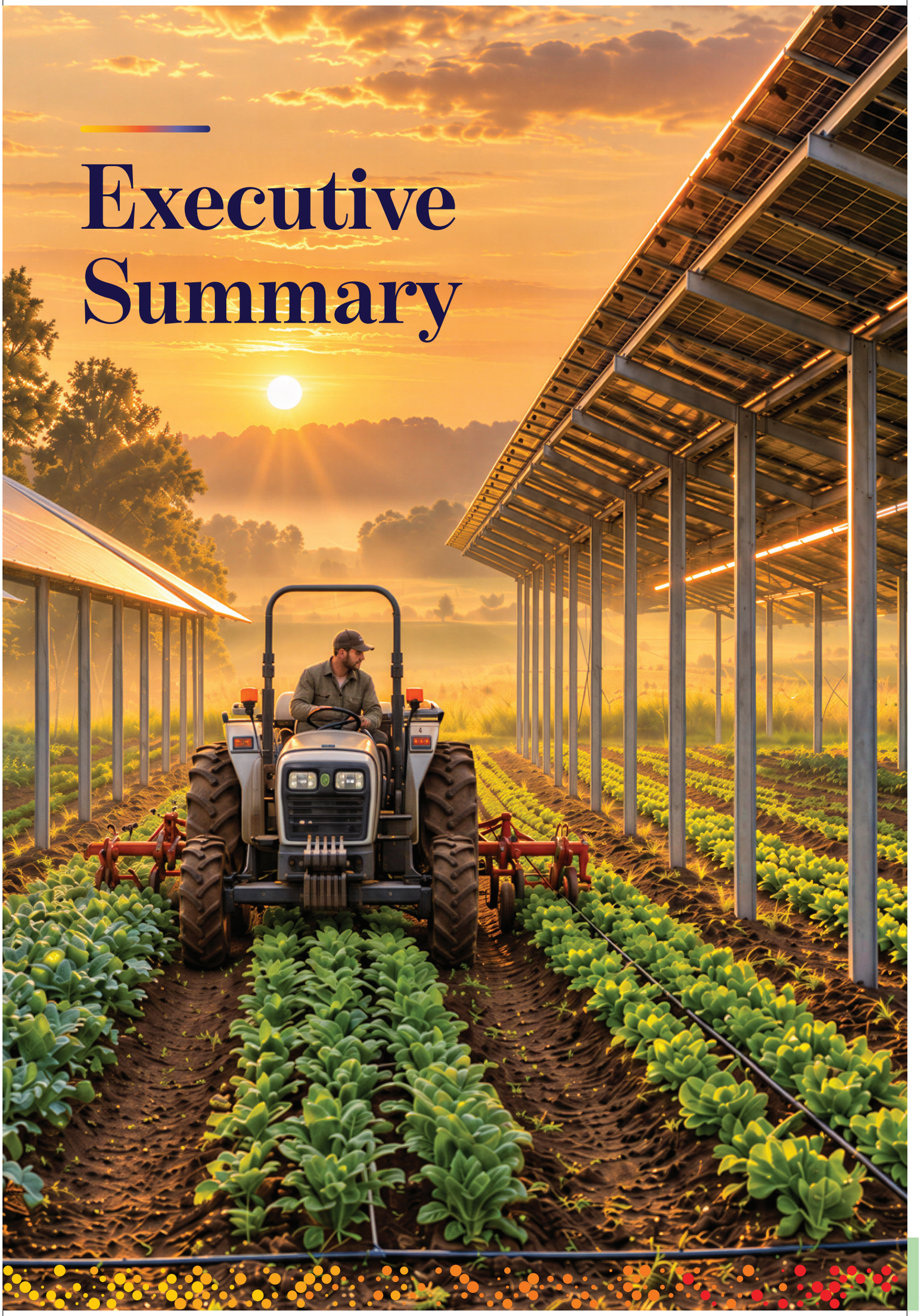
India's renewable energy journey demonstrates what sustained ambition and effective implementation can achieve. Non-fossil technologies accounted for 80% of India's new power generation capacity added over the past decade. In the last year alone, India added over 55 GW of non-fossil capacity, while non-fossil sources met around one-third of electricity demand during the first seven months of 2026. As the world's third-largest country in installed renewable energy capacity, India's experience offers valuable lessons for the Global South, with approaches that can be adapted to different national priorities and local needs.

Our experience also highlights the importance of placing farmers at the centre of the clean energy transition. Under PM-KUSUM, decentralised solar plants, solarised pumps and feeders, and models that enable farmers to participate in energy generation demonstrate how agricultural and energy policies can reinforce one another. Alongside pioneering work in countries such as Japan, France, Germany and Italy, these experiences offer valuable insights into the opportunities for integrating agriculture with solar energy.

The Global Agrivoltaics Climate-Zone Technical Framework addresses the need for a structured, climate-specific approach to planning and implementing such projects. It can help governments, farmers, developers, researchers and financiers make informed decisions, establish appropriate standards and move from isolated pilots towards wider adoption. I commend the International Solar Alliance, its Secretariat, and the experts and institutions whose contributions have made this initiative possible. I hope this Framework will strengthen international cooperation and help countries develop the evidence, policies and partnerships needed to scale up agrivoltaics.

The success of the energy transition must be measured not only by the clean power we generate, but also by the livelihoods we strengthen and the resources we preserve. By bringing food security, farmer prosperity and renewable energy together, agrivoltaics can help countries advance development without forcing a choice between competing needs. I am confident that this Framework will contribute to a more inclusive and resilient energy transition, creating lasting benefits for farmers, communities and future generations.

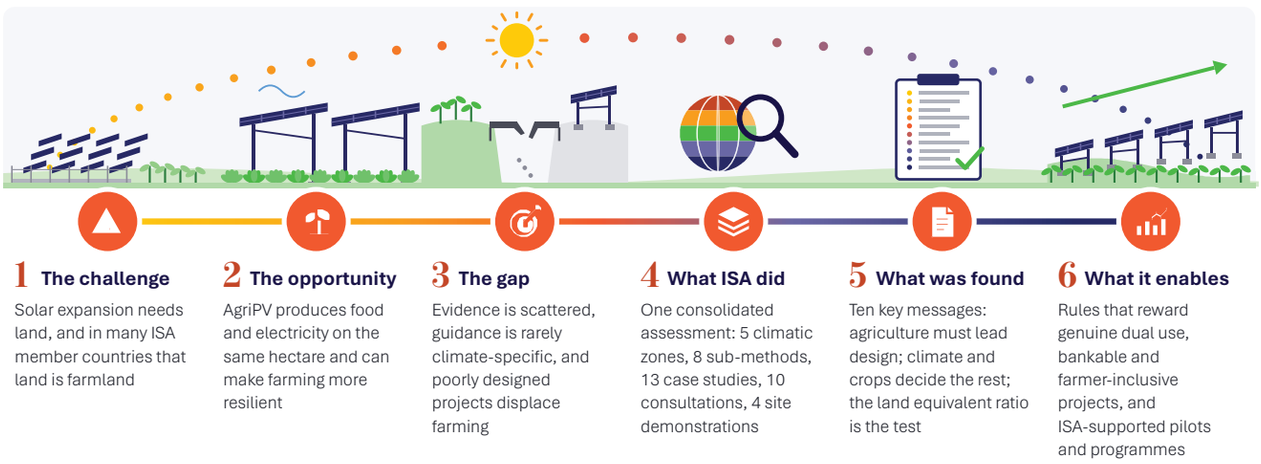
Executive Summary



EXECUTIVE OVERVIEW

Reconciling Energy and Food Production on Shared Land

Figure ES 1 · The logic of the framework, from challenge to action



The challenge. ISA member countries are expanding solar power at scale to meet climate, energy-security and development goals. Solar plants need land, and in many member countries the most suitable land is also farmland. Without a better model, the energy transition and food security will increasingly compete for the same hectares.

The opportunity. Agriphotovoltaics (AgriPV) produces electricity and food on the same land. Designed well, the panels become part of the farm: they cut heat stress, conserve soil moisture and shelter crops from hail, frost and heavy rain, while giving farmers a second source of income. Global capacity grew from about 5 MWp in 2012 to 18.4 GW by mid-2025.

The gap. Most experience is concentrated in a handful of countries and climates. Guidance is rarely differentiated by climate, projects are often designed around energy output with farming as an afterthought, and most member countries have no policy framework for distinguishing genuine dual use from solar plants with token cultivation.

What ISA has done. The International Solar Alliance commissioned this Framework, with PwC as technical consultant, to close that gap. It rests on one consolidated assessment covering five climatic zones, eight linked sub-methodologies, eight documented projects, stakeholder consultations spanning Asia, Africa, Europe, the Americas and the Pacific, site visits to operating plants and four worked demonstrations on real parcels in Egypt, India and Germany.

What it leads to. The Framework gives governments, developers, financiers and farmers a common, tested method to decide **where AgriPV fits, what to grow, how to design the system, whether it will pay, and which policies make it scale**, and gives ISA a foundation for supporting member countries from pilots to national programs (Figure ES 1).

PURPOSE OF THE FRAMEWORK

To enable ISA member countries to expand solar power on agricultural land **without sacrificing food production** — by providing a climate-responsive, agriculture-first method for assessing, designing, financing and regulating AgriPV, and by translating global experience into decisions that each country can take.

THE FRAMEWORK IN NUMBERS

18.4 GW
Global AgriPV capacity by mid-2025 from ~5 MWp in 2012

5
climatic zones analysed from subcategory of Köppen–Geiger climatic configuration

15–30%
water savings reported under partial shade in dry climates

LER 1.2–1.65
land equivalent ratio reported in documented case studies (above 1.0 = more productive than separate uses); site specific

16
operational challenges scored for probability and impact across five climate zones

15–50%
indicative capital cost premium over conventional solar, depending on structure height and design (about 15% at an operating Indian site)

8
sub-methodologies in one consolidated assessment

14
consultations with global developers, 10 virtual consultations and 4 physical visits

CENTRAL PROPOSITION

AgriPV is not solar engineering with crops placed underneath. It is an integrated land-use system in which agricultural productivity is the primary design driver, and energy yield, cost, constructability and safety are optimised within the boundaries agriculture sets.

That single inversion of the design sequence changes everything downstream: which crops are viable, how high the structure stands, how far apart the rows sit, what maintenance costs, how the project is financed, and whether the land ends up genuinely more productive than the two uses kept apart.

HOW THIS SUMMARY IS STRUCTURED

The summary follows the logic of the study itself: why AgriPV matters and what was done (Part A), what the assessment found (Part B), and what the findings make possible and how to act on them (Part C). Every finding is traced to the part of the methodology that produced it and to the key message it supports. Monetary values are given in Indian rupees (INR), with indicative US dollar (USD) equivalents at about INR 83 = USD 1 (Table ES 1).

Table ES 1 · How this summary is structured

Component	Question it answers	Sections
Ten Key Messages	What are the principal conclusions, and what do they imply for decision-makers?	Front matter
Part A: The Case and the Approach	Why is AgriPV needed, what gap does the Framework fill, and how was the assessment carried out?	1–3
Part B: Key Findings	What did the assessment find on climate, crops, design, field performance, risk, economics, business models and grid access?	4–11
Part C: From Findings to Action	What do mature markets do, what has the study delivered, what can countries achieve, and what should they do next?	12–15

TEN KEY MESSAGES

Principal Conclusions of the Framework

The ten messages below distil the Framework's findings into the conclusions of greatest consequence for AgriPV policy, program design and investment. Each message is elaborated, accompanied by its principal implication, and cross-referenced to the sections of this summary in which the supporting evidence is presented.

The same message numbers appear at the head of each section to maintain that linkage throughout the document. Technical terms and abbreviations are defined at first use; a full glossary is provided in the main report.

KEY MESSAGE

01 AgriPV has matured into an established solution to the land–energy challenge

Global installed AgriPV capacity rose from approximately 5 MWp in 2012 to 18.4 GW by mid-2025, with operating installations in China, India, Vietnam, Thailand, Kazakhstan, Malaysia, Austria, France, Germany, Italy, the Netherlands and Chile. This growth was driven by deliberate policy support in Japan, China, France, the United States, Germany and the Republic of Korea. When appropriately designed, AgriPV systems moderate temperature, retain soil moisture, reduce heat stress on crops and livestock and provide farmers with a diversified income, while generating clean electricity on land that remains in agricultural use.

> **Implication:** For ISA member countries, the question is no longer whether AgriPV is technically feasible, but how it can be deployed at scale in a manner that safeguards agricultural production.

Evidence and discussion: Sections 1, 7 and 13

02 Agricultural productivity must be the primary design driver

The Framework deliberately reverses the conventional solar design sequence. The strategic agricultural objective for the climatic zone is established first; crop selection then defines the light budget; mounting height, row spacing and panel density are derived from that budget; and energy yield, cost, constructability and safety are optimised within the resulting envelope. Crop height, shade tolerance, water requirements, mechanisation and farming practice are treated as binding constraints rather than variables to be traded away.

> **Implication:** Program eligibility and project approval should test whether design choices are demonstrably driven by agricultural requirements; otherwise projects risk becoming ground-mounted solar plants with token cultivation.

Evidence and discussion: Sections 1, 3 and 6

03 Climatic conditions define the AgriPV value proposition

Across the five Köppen–Geiger zones assessed, AgriPV addresses fundamentally different problems: maximum water conservation in arid zones; water saving and yield stability in semi-arid zones; protection from heat stress and intense rainfall in tropical zones; crop quality and protection from hail and frost in temperate zones; and season extension in continental zones. Each zone carries its own dominant design risk, structural priority, water strategy and maintenance regime. In hot, dry climates shade is the principal asset; in cool, cloudy climates light is the scarce resource that design must protect.

> **Implication:** National program should differentiate design standards, eligible crop lists and operation and maintenance (O&M) requirements by agro-climatic zone rather than apply a single national template.

Evidence and discussion: Sections 4 and 8

04 Crop selection is the foundational design decision

Crop choice determines panel density, row spacing and mounting height, and therefore the structure, cost and performance of the entire system. The Framework establishes a four-step method: an exhaustive longlist; a Go/No-Go gate on shade tolerance and height compatibility; weighted scoring against eight technical and economic criteria recalibrated to local constraints; and validation with farmers, agronomists and designers. Applied at four sites, the method selected medicinal and aromatic plants and garlic in Minya (Egypt), leafy greens and marigold in Hyderabad and ginger and floriculture in Himachal Pradesh (India), and berries in Rhineland-Palatinate (Germany). Shade-benefiting and shade-tolerant crops — leafy vegetables, herbs, spices, root crops and forages — offer the strongest synergies.

> **Implication:** A documented, auditable crop selection should be a mandatory component of every AgriPV project proposal.

Evidence and discussion: Section 5

05 No single system configuration is universally optimal

Elevated systems offer the greatest crop protection and water conservation but carry the highest structural cost. Vertical bifacial systems preserve machinery access and generate during morning and evening demand peaks, but at the demonstration sites produced only 53–66% of the specific yield of elevated fixed-tilt systems; a combination of vertical and tilted systems can be explored. Polyhouse systems provide full environmental control for high-value horticulture, at the highest capital cost and operational complexity. Within any configuration, design parameters function as agronomic instruments: a clearance of at least 2.5 m for farm machinery, at least 6 m between rows for combine harvesters, and tilt, orientation, inter-panel spacing and module type tuned to the crop.

> **Implication:** Policy should remain technology-neutral across configurations while requiring that the chosen configuration be justified against local agricultural priorities.

Evidence and discussion: Section 6

06 The net effect of shade is determined by design, water regime and soil

Shade imposes a cost, through reduced light for photosynthesis, and confers a benefit, through lower leaf temperature and reduced evapotranspiration. The net outcome is site specific. At Junagadh (India), a structure designed to minimize shading raised tomato yield by 150% and water-use efficiency by up to 152%. At the Central Arid Zone Research Institute (CAZRI) in Jodhpur, which has an arid climate, a dense fixed-tilt array reduced most crop yields by 5–12%, with the largest losses under full irrigation, where the moisture benefit is absent, whereas a redesigned row layout with gaps between modules turned mung bean yield positive. Studies in dry climates report water savings of 15–30%, and panel orientation alone reversed the yield outcome for mungbean in Nigeria.

> **Implication:** Agronomic claims should be supported by site-specific design analysis and field monitoring rather than generic assumptions about the benefits of shade.

Evidence and discussion: Section 7

07 The Land Equivalent Ratio is the benchmark of genuine dual use

As the panels are spaced to accommodate crops, AgriPV generates less electricity per unit of land than ground-mounted solar: 6% less at Gabersdorf (Austria), 33% at Jiangsu (China) and 60% at Västmanland (Sweden). This reduction is justified only where the combined agricultural and energy output exceeds what the same land would produce under separate uses, a Land Equivalent Ratio (LER) above 1.0. Documented values range from 1.2 in Sweden to 1.65 at Junagadh. The Swedish study also shows that retaining 70% of crop yield required rows of 9–11 m, which lowers the LER; the two tests must therefore be applied together.

> **Implication:** Regulators should adopt the LER, combined with a minimum agricultural output threshold, as the eligibility criterion for AgriPV incentives.

Evidence and discussion: Sections 7, 13 and 14

08 Operational and maintenance risks are significant, climate-specific and often underestimated

AgriPV combines the operational demands of a farm with those of a power plant. The Framework's risk assessment, which scores probability against impact separately for power generation and crop production, shows that high risks vary markedly by zone: extreme temperatures in arid and continental zones; reduced light and uneven terrain in temperate and continental zones; humidity, pests, disease and uneven water distribution in tropical zones; and snow and icing in continental zones. Transformer failure carries high impact in every zone and ammonia exposure from livestock and agricultural fields can affect overall energy yield, reducing module output by up to 10–15% within a few years.

Implication: O&M budgets, insurance cover, module standards and contractual obligations must be climate-specific; conventional solar maintenance practices will understate lifecycle cost.

Evidence and discussion: Section 8

09 AgriPV is financially viable, but ownership structure determines who benefits

An illustrative 10 MWdc project achieves a return to investors (equity internal rate of return, IRR) of 14–18%, a levelised cost of electricity (LCOE) of INR 3.5–5.0 per kWh (about USD 0.04–0.06), a debt service coverage ratio (DSCR) of 1.25–1.40 and a simple payback of 5–8 years. These figures are illustrative: returns depend on solar resource, project cost, crop choice and electricity and crop prices, and can vary widely between regions. Capital costs exceed those of ground-mounted solar — by about 15% at an operating Indian site, and indicatively by 20–50% depending on structure height and design. Electricity sales account for the majority of revenue (more than 90% in some cases) and underpin bankability; agricultural revenue sustains the legitimacy of the land use and the farmer's income. Keeping farming at the centre of AgriPV, eight business models are assessed, of which models owned by farmers or farmer producer organisations (FPOs) retain the most value on the farm but require capital and technical capacity, whereas developer- and utility-owned models reduce that burden but position farmers as lessors.

Implication: Blended and concessional finance, aggregation through farmer producer organizations and standardized revenue-sharing contracts are required to make inclusive ownership models bankable, while keeping farming at the centre.

Evidence and discussion: Sections 9 and 10



10 Enabling policy and appropriate deployment pathways are decisive for scale

Benchmarking of eight markets identifies four complementary policy pillars: regulatory clarity on dual land use, targeted financial incentives, alignment with national energy and agricultural strategies, and ecosystem support through research, standards, monitoring and capacity building. Markets combining all four, notably France, Japan and Germany, have scaled fastest. Grid readiness determines the appropriate pathway: for many ISA member countries, distributed and behind-the-meter AgriPV serving irrigation, cold storage and agro-processing offers a practical near-term route that avoids interconnection constraints, while utility-scale deployment depends on transmission planning and procurement frameworks.

Implication: Countries should progress from enabling regulations and pilot projects to support programs and market-led deployment, while strengthening all four policy pillars.

Evidence and discussion: Sections 11 to 14



PART A

The Case and the Approach



Part A sets the scene. It explains why AgriPV matters (Section 1), what the Framework sets out to do and for whom (Section 2), and how the assessment was carried out (Section 3). Together these sections establish the case and the method on which every finding in Part B rests.

01 The Strategic Case for Agriphotovoltaics

KEY MESSAGE 01

AgriPV has matured into an established solution to the land–energy challenge

KEY MESSAGE 02

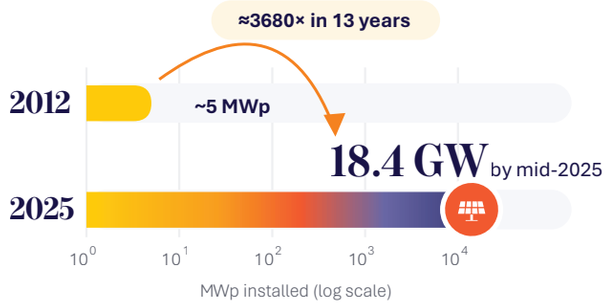
Agricultural productivity must be the primary design driver

ASSESSMENT BASIS

Phase A framing; Phase B evidence base (case studies and site visits)

This section explains the problem AgriPV addresses — competition between solar power and farming for the same land — what an AgriPV system is, and why a dedicated global framework is needed.

Figure ES 2 · Global installed AgriPV capacity, 2012 and 2025 (MWp = megawatts of peak solar capacity)



The Land–Energy Challenge

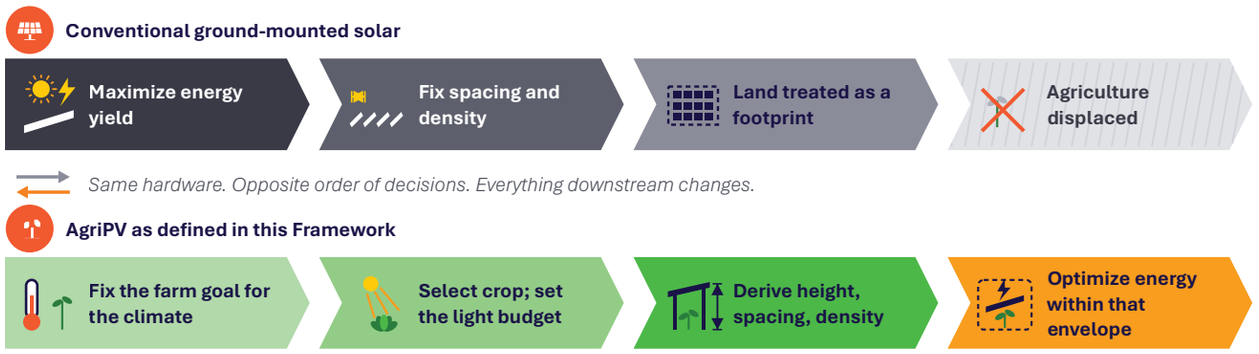
Solar power is expanding rapidly across ISA member countries, and national targets imply much more to come. Ground-mounted solar needs large areas of land, and the flat, sunny, accessible land that suits it best is very often productive farmland. In agrarian and land-constrained economies, converting that land to energy alone puts food production, rural livelihoods and public acceptance of solar at risk. Competition for land has become a binding constraint on the energy transition.

What an AgriPV System Is

An agriphotovoltaic (AgriPV) system produces electricity and food on the same land. Solar panels are mounted high above crops, set in upright rows with crops growing between them, or built into the roofs of greenhouses and polyhouses; some systems also shelter grazing livestock. What distinguishes AgriPV from a solar farm built on farmland is that **farming continues as a primary land use** and the solar structure is designed around it (Figure ES 2).

The idea was first proposed by Adolf Goetzberger and Armin Zastrow in 1981 and has since scaled rapidly, largely on the back of policy. Installed capacity rose from around **5 MWp in 2012 to 18.4 GW by mid-2025**, driven chiefly by incentives and frameworks in Japan, China, France, the United States, Germany and the Republic of Korea. Operating installations now span China, India, Vietnam, Thailand, Kazakhstan, Malaysia, Austria, France, Germany, Italy, the Netherlands and Chile.

Figure ES 3 · The order of design decisions in conventional solar and in AgriPV as defined by this Framework



The value proposition goes beyond electricity. The panels change the local climate beneath them: they cool the soil and crop, reduce the water lost to evaporation and shelter plants from hail, frost and heavy rain. The farmer gains a second income alongside crop sales. For agrarian and land-constrained economies, AgriPV therefore aligns renewable energy deployment with food security and climate adaptation in a single investment.

The Gap This Framework Fills

The promise of AgriPV is well established, but the knowledge needed to realize it is not evenly available. Experience is concentrated in a small number of markets — Japan, China, France, Germany, Italy and the United States — and in a limited range of climates. Most existing guidance is not differentiated by climate, although the right design in a desert differs fundamentally from the right design in a humid tropical or cold continental zone. Projects are frequently designed around energy output, with crops added afterwards, which risks lower yields, farmer resistance and land that is less productive than before. And most ISA member countries have no legal definition of AgriPV, no test of genuine dual use and no program to support it.

This Framework was commissioned to close these gaps. It consolidates global evidence into **one agriculture-first, climate-differentiated method** that any member-country can apply from screening a single parcel to designing a national program and it is explicit about where evidence is strong and where local validation is still required.

Reversing the Conventional Design Sequence

Conventional solar planning maximizes energy yield and treats land as a footprint. The Framework reverses the sequence: the farming objective for the climate is fixed first, the crop and the amount of light it needs follow, and only then are structure height, row spacing and panel density derived — with energy output optimized inside those limits (Figure ES 3).

AgriPV as a Platform for Rural Energy Integration

AgriPV can also anchor complementary technologies that put surplus solar power to productive use: **green hydrogen and battery storage**; **smart irrigation** and water management; **electric farm machinery** and rural mobility; **cold storage and agro-processing** that cut post-harvest losses; **decentralized microgrids** for farm clusters and rural enterprises; and **digital agriculture** using sensors, automation, robotics and artificial intelligence. Together these strengthen local energy resilience, reduce dependence on fossil fuels and create new sources of income across the rural economy.

02 Objectives, Scope and Intended Users

Having set out the case for AgriPV, this section defines what the Framework aims to achieve, the scope of its analysis and the readers it is written for.

The Framework's primary objective is comprehensive, climate-responsive guidance for the systematic planning, design and implementation of AgriPV across diverse climatic zones in ISA member countries, positioning AgriPV not as a niche experiment but as a **scalable, integrated land-use strategy** that advances renewable energy, agricultural productivity, water security and climate resilience together (Table ES 2).

Table ES 2 · Specific aims of the Framework

Specific aim	What it means in practice
Climate-specific guidance	Differentiated design and operational guidance for arid, semi-arid, tropical, temperate and continental zones, using Köppen–Geiger as the analytical foundation
Agriculture at the core	Crop characteristics, shade tolerance, water requirements and farming practice linked explicitly to structural and layout decisions
Configuration assessment	Suitability, benefits, trade-offs and application contexts of elevated, vertical and polyhouse AgriPV by zone and cropping system
Crop selection and prioritisation	A transparent method to identify crops that are agronomically viable, operationally compatible and economically attractive under partial shade
Operational challenges and mitigation	Climate-specific O&M challenges for both farm and PV system, with targeted mitigation for reliability, resilience and long-term performance

Intended Users of the Framework

Table ES 3 summarises the Framework's main user groups, the content most relevant to each and how they can apply it.

Table ES 3 · Intended users and how they can apply the Framework

User group	Most relevant content	Principal application
Government leadership and ISA National Focal Points	Key Messages 1, 7 and 10; Sections 12– 14	Establish national ambition and a coordinated energy–agriculture mandate
Regulators and policy institutions	Key Messages 2, 3 and 7; Sections 4, 7, 11–14	Design eligibility rules, permitting and incentive schemes
Utilities and distribution companies	Key Messages 8 and 10; Sections 8, 10– 11	Plan feeders, procurement and interconnection
Financiers and investors	Key Messages 8 and 9; Sections 8–10	Structure bankable, blended transactions
Developers, farmer organizations and farmers	Key Messages 4, 5 and 6; Sections 5–9 and 15	Screen sites and shape pre-feasibility



03 Overall Approach and Methodology

KEY MESSAGE 02

Agricultural productivity must be the primary design driver

With the objectives and users defined, this section explains how the assessment was carried out: four phases (A to D) and, at their core, eight linked sub-methodologies labelled M1 to M8. Every finding in Part B is traced back to these components.

AgriPV sits between two disciplines that normally judge projects differently: agronomy reasons from crop, soil and season; solar engineering from irradiance, yield and cost. The Framework's methodology forces the two to resolve against each other in a fixed sequence. It moves systematically from context definition (**Phase A**) through evidence building (**Phase B**) and assessment (**Phase C**) to synthesis and validation (**Phase D**), with agriculture positioned as the primary system driver throughout (Figure ES 4).

Phase A: Framing the Assessment

The objective was defined as climate-responsive guidance for policymakers, developers, farmers, financiers and ecosystem stakeholders. The **Köppen–Geiger classification** — which groups climates by temperature, precipitation and vegetation — was fixed as the analytical lens to ensure global applicability and scientific consistency. Five priority zones were selected. Polar climates were excluded as generally too cold for open-field agriculture, and the dry group was split into arid and semi-arid because their agronomic objectives differ materially. Critically, the **strategic agricultural objective for each zone was declared before any design work began** — water conservation in arid zones, heat-stress reduction in the tropics, season extension in temperate and continental climates.

Phase B: Building the Evidence Base

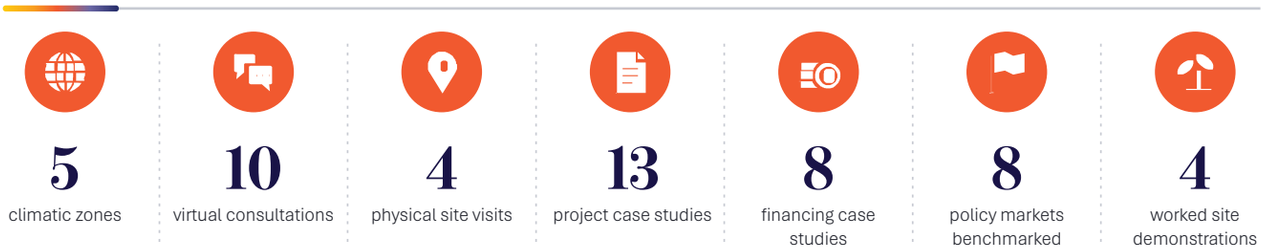
Secondary research drew on international policy frameworks, technology deployments, business models and operating experience, notably work on operations and maintenance best practice by the US National Renewable Energy Laboratory (NREL) and studies of maintenance across climates by the International Energy Agency Photovoltaic Power Systems Program



Figure ES 4 · The consolidated assessment methodology: four phases (A–D) and eight sub-methodologies (M1–M8)



Figure ES 5 · The evidence base behind the Framework



(IEA PVPS), together with technical literature and market data. Primary consultation covered the full value chain including policymakers, regulators, utilities, developers, technology providers, farmer producer organizations, agronomists, research institutions, financiers, industry associations and development agencies with experience spanning Japan, Europe, North America, Indonesia, Vietnam, Fiji, Jamaica, Egypt, Kenya and India. This included a joint consultation with Egypt's ministries of electricity, agriculture and water resources. Physical site visits covered operating systems from 10.8 kWp to 4.5 MWp in semi-arid, tropical and arid zones. Hypothetical sample sites were identified in every zone using geospatial tools, and all insights were triangulated against case studies, policy reviews and market data (Figure ES 5).

Phase C: The Eight Sub Methodologies

Phase C is where the assessment is performed. Each sub-methodology asks a defined question, applies a stated method and produces an output consumed by those that follow.

The Framework labels its eight sub-methodologies M1 to M8 (“M” stands for methodology). They are applied in a fixed order, and each uses the outputs of the one before: M1 defines the climate envelope; M2 tests whether a site within it is suitable; M3 selects the crops that suit the site; M4 designs the system around those crops; M5 and M6 set out how it must be operated and which risks

must be managed; M7 tests whether it is viable and who benefits; and M8 identifies the policy conditions needed to scale it up.

These labels are used throughout this summary. The "Assessment basis" banner at the start of each section in Part B shows which sub-methodologies support its findings, and the table at the end of this section maps each one to the finding and key message it produced. Table ES 4 sets out, for each sub-methodology, the question it answers, the method applied and the output it produces.

Table ES 4 · The eight sub-methodologies (M1–M8)

Sub-methodology	Core question	Method applied	Output
M1 **Climatic zone characterisation**	What are the agro-climatic conditions, and how do they affect crops and panels?	Long-term temperature, diurnal range, humidity, rainfall seasonality, wind and radiation; effects on germination, flowering, disease, water demand, soiling, heat loss and structural load; array-induced microclimate	Zone envelope for all later decisions
M2 **Site suitability assessment**	Does this parcel have reasonable agriculture–energy compatibility?	Six-step logic from boundary confirmation to rating; five-category minimum data pack; remote screening with land-use overlays, digital elevation models and solar resource tools	Suitability rating with explicit confidence level
M3 **Crop selection and prioritisation**	Which crops are viable, compatible and attractive under partial shade?	Longlist → Go/No-Go gate on shade and height → weighted scoring on eight criteria, recalibrated to site → validation with agronomists and farmers	Ranked, classified crop list
M4 **Design configuration and integration**	Which configuration and geometry serve the crop in this zone?	Clearance, density, layout; module technology, fixed tilt vs trackers, durability; water strategy; irrigation, machinery and livestock integration	Zone design guidance and cross-zone matrix
M5 **O&M comparison and adaptation**	How does operating AgriPV differ from conventional solar?	ground-mounted system O&M baseline reviewed against added requirements from crops; each requirement re-expressed per zone	Climate-differentiated O&M regime
M6 **Challenge and risk assessment**	Which challenges need action now, which only monitoring?	Probability and impact rated High/Medium/Low (1–3), impact scored separately for power and crops; score = P × I	Risk profile per challenge per zone
M7 **Techno-commercial assessment**	When does a project become viable and bankable?	Line-item capex and opex; explicit assumption set; cost of electricity (LCOE), land equivalent ratio (LER), net present value (NPV), internal rate of return (IRR), debt service coverage ratio (DSCR) and payback; revenue, ownership and financing options compared	Indicative outcome ranges with assumptions
M8 **Policy and best-practice benchmarking**	Which enabling conditions separate mature from stalled markets?	Review of regulation, incentives, strategy and ecosystem support in France, Italy, Japan, Germany, India, Kenya, Australia and the USA	Four policy pillars and best practices

How risk was scored (M6). Challenges were identified from the NREL and IEA PVPS literature and from stakeholder consultation. Each was rated for probability of occurrence and for impact severity — the latter separately for power generation and for crop production — on a three-point scale (Low 1, Medium 2, High 3). Multiplying the two gives a score classified as high (7–9), medium (4–6) or low (1–3). Because impact is scored for both sides of the project, a challenge can be benign for the PV plant yet critical for the crop — precisely what conventional solar risk registers miss.

Phase D: Synthesis and Validation

Outputs were consolidated into a cross-zone design matrix, transferable design principles, policy recommendations and a screening toolkit. Validation is what distinguishes a tested method from an assertion: the complete crop-selection method was **re-applied end to end at four real locations** — a 4.0-ha parcel in Minya, Upper Egypt (arid); a 0.25-ha peri-urban plot in Hyderabad, Telangana (tropical); a 0.25-ha terraced plot at Jahu, Himachal Pradesh (temperate); and a 5.0 hectare arable parcel at Grafschaft, Rhineland-Palatinate, Germany (continental). Each runs the longlist, gate, recalibrated weights and scoring on local data, and shows every recalibration explicitly rather than assuming it.

From Methodology to Findings

Each part of the methodology answers a defined question and produces a finding that underpins one or more of the key messages. The map below shows that chain; the same references appear in the banner at the head of each section in Part B (Table ES 5).

Table ES 5 · From methodology to findings

Assessment component	Question answered	Principal finding	Key message	Section
M1 **Climatic zone characterisation**	How do climate conditions shape crops and panels?	Each zone needs a different AgriPV proposition: shade is an asset in dry zones, light is the scarce resource in cool zones	03	4
M2 **Site suitability assessment**	Is this parcel compatible with both uses?	Suitability must be established before engineering, on a minimum data pack, with an explicit confidence level	04	5
M3 **Crop selection and prioritisation**	Which crops are viable and attractive under shade?	Crop choice fixes the design; shade-tolerant groups perform best; scoring weights must be recalibrated to each site	04	5
M4 **Design configuration and integration**	Which configuration and dimensions serve the crop?	No universal configuration; design parameters are agronomic instruments; vertical systems give 53–66% of elevated output per kWp	05, 02	6
Phase B evidence base	What happens on operating projects?	The effect of shade depends on design, water regime and soil; AgriPV yields less power per hectare but a land equivalent ratio above 1.0	01, 06, 07	7
M5 **O&M comparison and adaptation**	How does operating AgriPV differ from conventional solar?	Maintenance must be adapted to crops and climate; conventional practice understates lifecycle cost	08	8
M6 **Challenge and risk assessment**	Which risks matter most, and where?	High risks differ sharply by zone; transformer failure is high-impact everywhere; ammonia from livestock can cut module output	08, 03	8
M7 **Techno-commercial assessment**	When is a project viable and bankable, and who benefits?	Projects can be viable and bankable under illustrative assumptions, with site-specific returns; electricity drives bankability; ownership decides farmer benefit	09	9–11
M8 **Policy and best-practice benchmarking**	What enabling conditions separate mature markets?	Four policy pillars; distributed and behind-the-meter systems as the practical near-term pathway	10	11–12
Phase D validation	Does the method work on real sites?	Applied to four contrasting parcels, the method produces distinct, defensible crop and design recommendations	04, 05	5–6

SCOPE LIMITATIONS OF THE METHODOLOGY

It produces **screening-grade, not investment-grade** outputs. It does not replace detailed engineering, structural analysis or agronomic planning; it does not model each country's land classification, tariff or approval regime; and it does not substitute for project-specific financial modelling and due diligence. Field-level AgriPV data remains thin in many regions, so where proxies were used, outcomes may differ at scale.

PART B

Key Findings



Part B presents what the assessment found. It follows the order in which an AgriPV project is planned: climate (Section 4), site and crops (Section 5), system design (Section 6), field evidence (Section 7), operation and risk (Section 8), economics (Section 9), business models and finance (Section 10) and grid access (Section 11). Each section opens with the key messages it supports and the sub-methodologies behind it.

04 Climatic Zones as the Organising Principle

KEY MESSAGE 03

Climatic conditions define the AgriPV value proposition

ASSESSMENT BASIS M1

Climatic zone characterisation

Every AgriPV decision starts with climate. Applying sub-methodology M1, this section shows how the five climatic zones shape what AgriPV should achieve — the foundation for all the sections that follow.

The Framework organizes all of its advice by climate, using the **Köppen–Geiger classification,** the internationally recognized system that groups the world's climates by temperature and rainfall. Five zones are covered: **tropical** (group A), **arid and semi-arid** (the two parts of the dry group B, treated separately because their farming goals differ), **temperate** (group C) and **continental** (group D). Polar climates are excluded because they are generally too cold for open-field agriculture. Many sites sit on the boundary between two zones; the zone profiles should then be read together and adapted locally.

For every zone, the Framework works through four linked questions: the environmental and agricultural conditions; which crops suit the site and how they are farmed; which system configuration fits; and which operational challenges arise and how to mitigate them. Figure ES 6 condenses the answers.

HOW THE PANELS CHANGE THE GROWING ENVIRONMENT IN EACH ZONE

In **arid** zones, panels shade the soil and cut evaporation, creating a cooler, more humid environment that conserves water and protects crops from heat stress. In **semi-arid** regions they damp temperature swings and wind, improving moisture retention and limiting erosion. In the **tropics** they shield crops from excess radiation and intense downpours, preventing leaf scorch and soil erosion. In **temperate** zones they buffer early frost and summer heat, extending the growing season. In **continental** climates they buffer both summer heat and winter cold but can delay the warming of soil in spring, shortening an already brief season.

In hot, dry climates, shade is not a cost to be minimized; it is the primary asset. In cool, cloudy climates, light is the scarce resource, and design must protect it.

Figure ES 6 · The AgriPV proposition by climatic zone (Köppen groups: BW = desert, BS = steppe)

	ARID	SEMI-ARID	TROPICAL	TEMPERATE	CONTINENTAL
Köppen group	B (BW)	B (BS)	A	C	D
Climate signature	<250 mm rain; evaporation ≫ rain	250–500 mm; erratic rainfall	20–35 °C year-round; humid, intense sun	−5 to 30 °C; 500–1,500 mm	Winters < −30 °C; short season
Primary AgriPV goal	Maximum water conservation	Water saving + yield stability	Heat-stress & rain protection	Crop quality, hail & frost cover	Season extension, frost protection
Dominant design risk	Heat, dust, salinity	Erosion, variable rain, livestock	Humidity, disease, corrosion, storms	Low seasonal light, hail, machinery	Snow load, frost, large machinery
Lead configuration	Elevated canopy	Elevated / vertical + windbreaks	Elevated (ventilated) + polyhouse	Elevated & vertical	Vertical bifacial; snow-shedding
Anchor crops	Leafy greens, herbs, aromatic plants, garlic	Sorghum, millet, legumes, forage	Coffee, cocoa, spices, leafy greens	Berries, leafy veg, root crops	Early greens, berries, cereals
Water strategy	Drip / sub-surface; runoff capture	Rainwater harvest; soil cover	Drainage; controlled runoff	Soil-moisture monitoring	Snowmelt storage; drought buffer
O&M emphasis	Frequent waterless cleaning; cooling	Periodic cleaning; erosion checks	Anti-corrosion; vegetation; sealing	Seasonal cleaning; de-icing	Snow removal; freeze–thaw checks



05 Site Suitability and Crop Selection

KEY MESSAGE 04

Crop selection is the foundational design decision

ASSESSMENT BASIS M2

Site suitability assessment; M3 Crop selection and prioritization; Phase D validation (worked site demonstrations)

Within a climatic zone, the next questions are whether a specific parcel is suitable and which crops it should grow. This section applies M2 (site suitability) and M3 (crop selection); the crops chosen here set the design requirements addressed in Section 6.

Site Suitability Before Engineering

Before any design work, the Framework asks whether a parcel, farm cluster or target area has reasonable compatibility between farming and energy production, and whether there is enough evidence to justify detailed engineering. The assessment follows six steps (Table ES 6).

Table ES 6 · The six-step site suitability assessment

Step		What is assessed
1	**Confirm the site boundary**	Exact boundary or coordinates. If only a broad region is known, the result must be labelled a regional screening, not a site assessment
2	**Establish current agricultural use**	Crop calendar, crop heights, row spacing, machinery, irrigation practice and key seasonal operations
3	**Assess physical conditions**	Slope, terrain, drainage, flood risk, access routes, nearby obstructions, soil characteristics and land-use restrictions
4	**Assess solar and grid conditions**	Solar resource, shading, distance to the grid and likely connection route, and existing infrastructure
5	**Check farming–solar compatibility**	Machinery clearances, row spacing, maintenance access and movement of farm equipment
6	**Assign a suitability rating**	A formal rating with a stated confidence level, separating confirmed findings from those inferred remotely or from stakeholders

A credible assessment rests on a **minimum data pack** in five categories: geotechnical and topography (soil, slope, subsurface conditions); hydrology (water source and rights, water quality, drainage and flood risk); meteorology (solar resource, wind and snow loads, local weather hazards); agriculture (soil health and existing farming); and infrastructure (site access, grid connection point, obstructions). **Remote screening** — mapping the boundary, overlaying land-use data, assessing terrain from digital elevation models, estimating the solar resource with standard tools and reviewing historical imagery — is a cost-effective first pass, provided every assumption is recorded and rated for confidence.

Figure ES 7 · The four-step crop selection process and the three classes of crop response to shade (curves are schematic; RSR = reduction in solar radiation)



Why Crop Choice Comes First

Crops differ in how much shade they tolerate, how much water they need, how tall they grow and whether they can be farmed by machine. Crop choice therefore drives the entire system design: it sets the amount of light the array must let through, which in turn fixes panel density, row spacing and structure height. The Framework's four-step process makes that choice explicit and auditable. Two **non-negotiable tests** act as a Go/No-Go gate before any scoring: the crop must tolerate the shade the structure will cast without unacceptable loss of yield or quality, and its height and canopy must fit the planned clearance, row spacing, farm access and maintenance needs. Crops that fail either test proceed only as clearly labelled experimental trials (Figure ES 7).

Shade Tolerance of Major Crop Groups

The Framework's review of crop physiology indicates which crop groups are most likely to succeed under panels. Percentages show the approximate reduction in sunlight each group can tolerate without significant yield loss (Table ES 7).

Table ES 7 · Shade tolerance of major crop groups

Crop group	Shade tolerance	Suitability for AgriPV
Leafy vegetables	Shade-tolerant to about 40% (spinach, cabbage, lettuce)	Excellent fit; shade often improves leaf size and quality
Herbs, medicinal and aromatic plants	Mint and chamomile to about 40%; lavender about 20%	Good fit; shade can raise essential-oil quality
Spices	Black pepper, turmeric, ginger to about 40%; chilli, cumin about 20%	Strong fit, especially in tropical zones
Beverage crops	Coffee, cocoa and tea to about 50%; traditionally grown under canopy	Excellent fit in tropical zones
Root and tuber crops	Cassava, yam and taro highly tolerant; potato and sweet potato to about 40%	Good fit; foundations must stay clear of harvesting machinery

Table ES 7 (continued) · Shade tolerance of major crop groups

Crop group	Shade tolerance	Suitability for AgriPV
Forage and fodder	Alfalfa, clover and grasses to about 25–50%	Good fit; panels also shade grazing livestock
Fruits	Berries 30–50% (shade-benefiting); banana and mango about 30%; apple, grape and citrus about 20%	Berries strong; tree height limits orchard crops
Cereals	Wheat, barley and oats to about 50% (with some yield loss); sorghum and millet about 30%; maize shade-susceptible	Small grains feasible, often under vertical arrays; maize generally unsuitable
Fruiting vegetables	Tomato and pepper need strong light for fruit set	Only with light-managed designs; yields fall under heavy shade
Pulses and oilseeds	Chickpea, lentil, soybean, sunflower and rapeseed shade-susceptible; peas and beans about 20%	Generally unsuitable except peas and beans under light shade
Fibre and sugar crops	Cotton and sugarcane shade-susceptible; sugar beet about 20%	Low suitability; sugarcane also too tall

By zone, tropical systems suit coffee, cocoa, banana, cassava, black pepper and ginger; dry climates favour forages, sweet potato, leafy vegetables and salt-tolerant crops where soils or water are saline; temperate climates offer the widest range, including berries, leafy vegetables, root crops and forages; and continental climates allow shade-tolerant cereals such as wheat and barley alongside forages, within a short season. The importance of each selection criterion also shifts by zone: water-use efficiency dominates in dry zones, disease resistance in humid tropics, and frost protection and season extension in cool climates.

Weighted Scoring and Site Specific Calibration

Crops that pass the gate are scored from 1 (poor fit) to 5 (excellent fit) on eight criteria: resilience to climate stress, ease of mechanisation, water and irrigation needs, value in crop rotation, labour intensity, crop lifespan, market demand and value, and existing area under cultivation. Each criterion carries a weight that reflects the site's binding constraints, giving a total score out of 500. The four worked demonstrations show why the weights must change with the site: water rises to 25% where groundwater or Nile irrigation quotas are limiting and falls to 5% in rain-fed Rhineland; mechanisation drops to 5% on smallholdings with plentiful labour; and climate resilience rises to 30% where protection from hail, frost and rain is the main benefit (Figure ES 8).

The results are instructive. In **Minya (Egypt), medicinal and aromatic plants** such as basil, chamomile, mint and marjoram (410) and garlic (405) lead: they gain from shade, use little water and command high export prices. In **Hyderabad (India)**, leafy greens (415) and marigold (410) win under a groundwater crisis, and the analysis points the site away from water-intensive paddy rice. In **Jahu, Himachal Pradesh (India)**, ginger and floriculture tie (415), exploiting off-season prices and protection from hail and frost. In **Grafschaft (Germany)**, all finalists score in a narrow 350–375 band — a direct measure of how scarce light limits the benefit of shade in cool climates — with berries leading and the existing arable rotation better suited to vertical than overhead arrays. Each crop is finally classified as recommended, conditionally **recommended, a pilot candidate or not recommended**, after validation with local agronomists, farmers and market data.

Figure ES 8 · Scoring weights recalibrated at the four demonstration sites, with the top-ranked crops at each (score out of 500)

	Illustrative default	Minya, Egypt (arid)	Hyderabad, India (tropical)	Jahu, India (temperate)	Grafschaft, Germany (continental)
Climate resilience	20%	20%	20%	25% ▲	30% ▲
Market demand / value	25%	25%	25%	25%	25%
Water & irrigation	15%	25% ▲	25% ▲	10% ▼	5% ▼
Ease of mechanisation	15%	5% ▼	5% ▼	5% ▼	10% ▼
Area under cultivation	10%	10%	5% ▼	15% ▲	5% ▼
Rotation & intercropping	5%	5%	10% ▲	10% ▲	10% ▲
Labour intensity	5%	5%	5%	5%	10% ▲
Crop lifespan	5%	5%	5%	5%	5%
Top-ranked crops (score / 500)	—	Medicinal & aromatic plants 410; garlic 405	Leafy greens 415 Marigold 410	Ginger 415 Floriculture 415	Berries 375 Leafy salads 370

06 System Parameters Configuration and Design

KEY MESSAGE 05

No single system configuration is universally optimal

KEY MESSAGE 02

Agricultural productivity must be the primary design driver

ASSESSMENT BASIS

M4 Design configuration and integration; Phase D validation (worked site demonstrations)

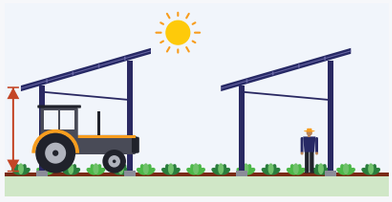
With crops selected, the system is designed around them. Applying M4, this section compares the three principal configurations and the design parameters that control light, water and machinery access.

The Framework evaluates three principal configurations against crop type, climate, mechanisation, energy output and cost (Figure ES 9).

Elevated AgriPV mounts panels typically 2–3.5 m above the ground, forming a continuous canopy with full farming beneath. It protects crops and conserves water best, but the tall structures needed to resist wind and snow raise the cost per unit of capacity, and cleaning at height may require lifts or robotic cleaners. Vertical bifacial AgriPV installs double-sided panels upright in rows facing east and west. It preserves access for machinery, acts as a windbreak and generates most in the morning and evening, when demand is often high; it needs stronger columns against wind and more land per megawatt. Polyhouse AgriPV integrates modules into the roof of a controlled-environment structure for high-value horticulture and year-round production, at the highest capital cost and with demanding heat management.

Figure ES 9 · The three principal configurations compared (relative ratings drawn from the Framework's assessment)

Elevated AgriPV

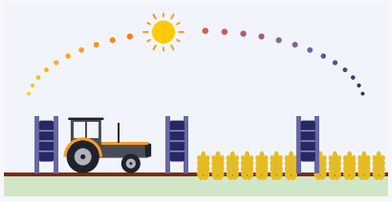


2–3.5 m continuous canopy

Crop & weather protection	●●●
Water conservation	●●●
Machinery access	●●○
Energy yield per kWp	●●●
Capital cost (higher = more)	●●●
O&M complexity	●●●

Harsh-climate horticulture; water-scarce, high-value crops

Vertical bifacial AgriPV

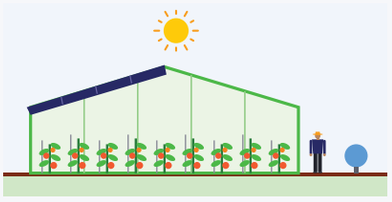


Panels mounted upright on posts, E–W facing

Crop & weather protection	●○○
Water conservation	●○○
Machinery access	●●●
Energy yield per kWp	●○○
Capital cost (higher = more)	●●○
O&M complexity	●○○

Mechanized arable farms; morning/evening peak demand

Polyhouse AgriPV



PV integrated into roof

Crop & weather protection	●●●
Water conservation	●●●
Machinery access	●○○
Energy yield per kWp	●●○
Capital cost (higher = more)	●●●
O&M complexity	●●●

Premium year-round crops with controlled environment

PRINCIPAL DESIGN TRADE-OFF

Systems that enhance crop quality and conserve water require higher investment and expertise; systems that maximise machinery access and energy output give up some environmental control. The right choice depends on whether a project prioritises resource efficiency in a constrained environment, operational scale, or intensive high-value production.

Design Parameters and Their Agronomic Function

Once the crop and configuration are fixed, a small set of design levers decides whether the system serves agriculture or merely occupies it. Row spacing governs light and machinery access: about 6 m or more for combine harvesters and 5 m for small tractors. Structure height sets clearance and airflow: 2.5 m or more to pass tractors and harvesters. Tilt and orientation, set using a sun-path diagram for the site, shape the pattern of shade, rain runoff, snow shedding and wind loading. Gaps between panels fine-tune the light and rain that reach the soil. Module type, such as opaque, semitransparent or bifacial, governs which crops are viable. Reflectors can redirect light into shaded strips, and gutters can harvest rainwater from the panels for irrigation (Figures ES 10 and 11).

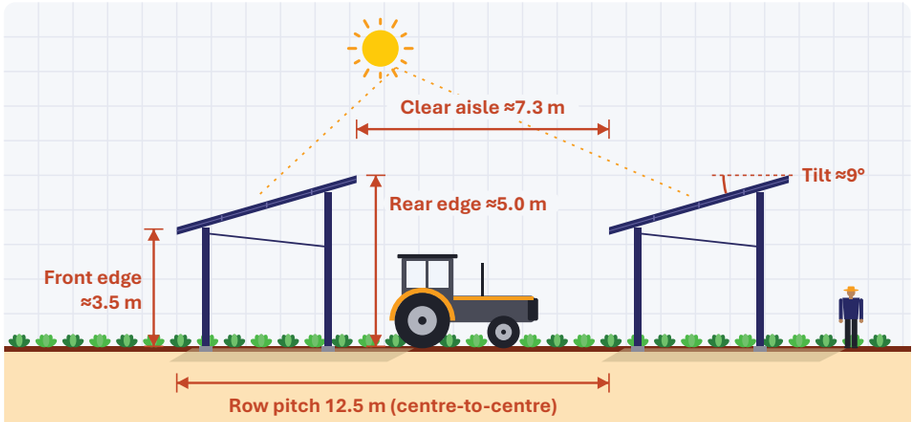
Configuration has a clear energy price. At the demonstration sites, vertical bifacial arrays produced **53–66% of the electricity per unit of capacity** of elevated fixed-tilt systems. That is acceptable where machinery access, peak-time generation or snow shedding matter more than volume but it must be reflected in the business case from the outset.

Trackers that turn panels to follow the sun can raise output by 15–25% (single-axis) or 30–35% (dual-axis) compared with fixed panels, and can be programmed to give crops more light in the morning and evening and more shade at midday. They add mechanical complexity, cost and wind-load requirements.

Solar Technology Options

Module choice should serve both farm and energy goals. **Bifacial** modules, which generate from both faces, benefit from light reflected by crops and light-coloured soils, and perform especially well over snow. **Half-cut**

Figure ES 10 · Key dimensions of the reference AgriPV design used in the Framework's simulations



Reference design basis used for the Framework's energy simulations (4-panel portrait table, fixed tilt, south-facing). Values are illustrative, not prescriptive.

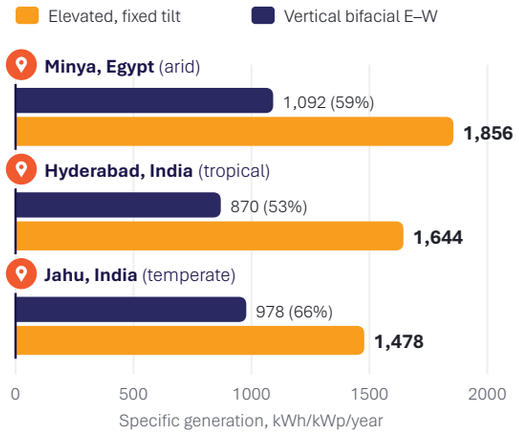
≥ 2.5 m clearance
to pass tractors, sprayers, harvesters

≥ 6 m between rows
for combines and turn-arounds

≥ 5 m for small
tractors / hand tools

Ground coverage
30–50% of land; ≈25% of light reaches the crop zone

Figure ES 11 · Simulated annual electricity per unit of installed capacity (kWh per kWp), elevated and vertical systems, at three demonstration sites



cell designs are more resilient to partial shading. **Semitransparent** modules, made by spacing cells further apart or thinning the active layer, let a controlled share of light through to crops at the cost of lower output per panel; **transparent** modules based on thin-film, organic, dye-sensitised or perovskite technologies go further but are less efficient. **Glass-on-glass** construction gives the durability needed outdoors, and **flexible** thin-film modules open up curved polyhouse roofs and tensile shade structures.

System Sizing and Grid Constraints

Unlike conventional plants, AgriPV capacity is not maximized for the land available; it follows from the structural layout chosen to accommodate crops and machinery. Inverter capacity is normally set below panel capacity, at a DC/AC ratio of 1.1–1.4, so that inverters run near peak efficiency. Where projects connect to rural networks, the grid operator's maximum injection limit at the local substation may cap project size, and new connecting lines raise right-of-way challenges: public acceptance, statutory clearances, land acquisition and difficult terrain.

Safety, Electrical Integration and Technical Standards

Because farm workers, machinery and livestock operate beneath and around live electrical equipment, safety requirements are more demanding than for conventional solar plants. The Framework references international standards for each element of the system (Table ES 8).

Table ES 8 · Safety requirements and reference standards

Area	Key requirements	Reference standards
Electrical safety	Redundant earthing; correctly rated fuses and breakers; clearly marked isolation switches with lockout–tagout procedures during maintenance	IEC 60364; IEC 60947
Mechanical safety	Structures engineered for local wind, dust-storm and snow loads; clearances for machinery and people; periodic torque checks on bolts and clamps	IEC 61215
Operational safety	Safety training for farm and maintenance staff; durable warning signage; fire suppression near inverters and batteries	Local safety codes
Cabling	UV-resistant, double-insulated solar cables and weather-tight connectors; armoured or conduit-protected underground routing, clear of ploughing depth and rodents	IEC 60364-7-712; IEC 62930; IEC 62852; IEC 60502; IEC 61386
Inverters	95–99% conversion efficiency; multiple maximum-power-point trackers for partly shaded arrays; IP65 or better dust and water protection; grid-code compliance; remote monitoring	IEC 60529; IEC 62109
Battery storage	Lithium iron phosphate chemistry (6,000–10,000 cycles; 85–95% round-trip efficiency); battery management system; thermal management; fire-rated enclosure	IEC 62619; IEC 62485; NFPA 855

07 Evidence from Field Deployments

KEY MESSAGE 06

The net effect of shade is determined by design, water regime and soil

KEY MESSAGE 07

The Land Equivalent Ratio is the benchmark of genuine dual use

ASSESSMENT BASIS

Phase B evidence base (case studies and site visits)

Sections 4 to 6 set out the method. This section tests it against what operating projects and field trials have actually achieved, drawing on the Phase B evidence base.

The Framework reconciles apparently contradictory results from India's leading trials. At the Central Arid Zone Research Institute (CAZRI) in Jodhpur, a dense fixed-tilt desert array reduced yields for almost every crop in the shaded inter-row, and the losses were sharpest for winter crops grown under full irrigation where water was not limiting, the moisture benefit of shade was switched off and only the light cost remained. On sandy soils that hold little water, shade saves little. At Junagadh Agricultural University, a structure computer-designed to minimise shading, with a shade-tolerant crop on water-retentive black soil, delivered gains. **Same crop family, opposite signs — because of design, irrigation and soil (Figures ES 12 and 13)**.

The energy side shows the mirror image. Because AgriPV spaces panels for crops, it produces less electricity per square metre of land — **6% less at Gabersdorf, 33% at Jiangsu and 60% at Västmanland**. At Jiangsu, the capacity utilisation factor was 13.7% against 15.3% for an equivalent ground-mounted plant, and the site would

Figure ES 12 · Reported crop-yield effects under AgriPV compared with open-field farming (Jodhpur: CAZRI trials; Junagadh: JAU trial; Sagar: operating farm)

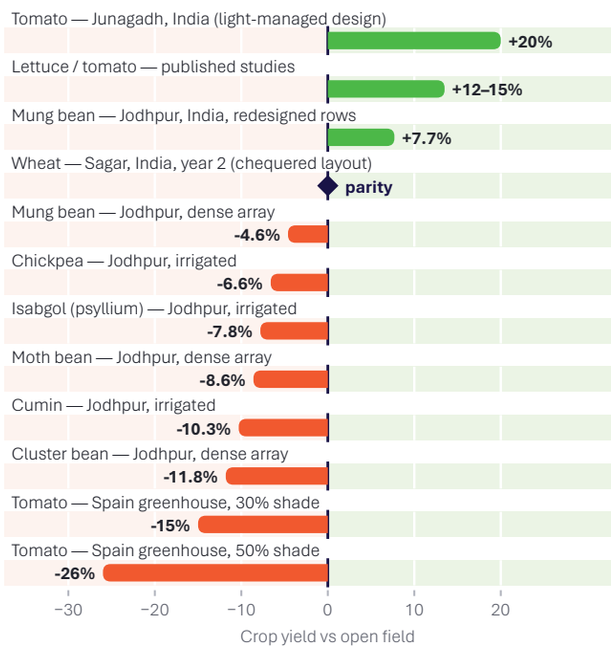
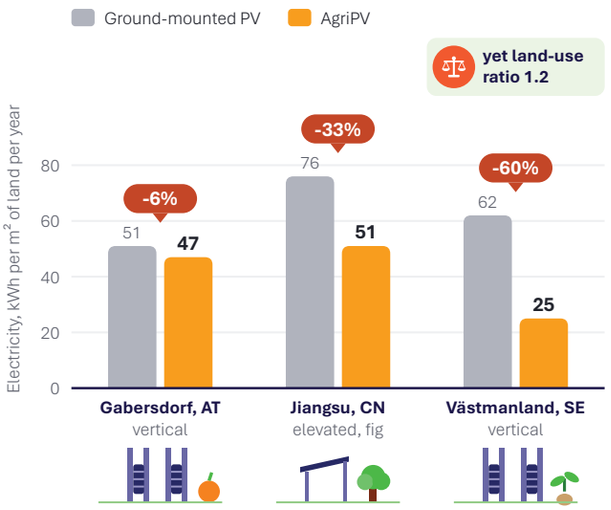


Figure ES 13 · Electricity per square metre of land, AgriPV compared with conventional ground-mounted solar



have produced about 48% more power had it been dedicated to PV.

That is the price of dual use, and the **land equivalent ratio** is the test of whether it is worth paying. Västmanland's LER of 1.2 and Junagadh's of up to 1.65 confirm that combined food and energy output exceeds what the same land would give under separate uses. The Swedish study also shows the design tension precisely: holding 70% of open-field yield required widening rows to 9 m for oats and 11 m for potatoes, which lowers LER. Regulators should therefore set LER and minimum-yield tests together.

Summary of Documented Projects

Table ES 9 summarises the documented projects behind these findings, with their zone, capacity, configuration, crops and key results.

Table ES 9 · Summary of documented projects

Project	Zone	Capacity	Configuration and crop	Key result
Sagar, Madhya Pradesh, India	Semi-arid	4.5 MWp (2025)	Elevated, 3.5 m clearance, 8 m row spacing; built under Component A of PM-KUSUM, India's national farmer solar program	Tomato, broccoli, lettuce, papaya thrive; wheat reached 100% of open-field yield in year 2 with 25–30% water saving; capital cost about 15% above conventional solar; utility payment delays
Junagadh Agricultural University (JAU), Gujarat, India	Semi-arid	7.2 kWp (2022)	Elevated, designed to minimise shading	Tomato +150%; water-use efficiency +152% (cucumber), +60% (cherry tomato); land equivalent ratio up to 1.65

Table ES 9 (continued) · Summary of documented projects

Project	Zone	Capacity	Configuration and crop	Key result
Central Arid Zone Research Institute (CAZRI), Jodhpur, India	Arid	105 kW (2017)	Dense fixed-tilt, three experimental blocks	Most crops −5% to −12% in shaded inter-rows; mung bean turned +7.7% under a redesigned layout
Jiangsu, China	Humid subtropical (Köppen Cfa)	20 MW (2016)	Elevated; figs between rows; tourism	24 GWh a year; capacity utilisation 13.7% against 15.3% for conventional solar; about 48% more power had the land been used for solar alone
Gabersdorf, Austria	Temperate	2 MWp (2023)	Vertical bifacial over 5.1 ha; pumpkin	Over 2 GWh/yr while cultivation continues between rows
Västmanland, Sweden	Continental	22.8 kW (2020)	Vertical bifacial; potato and oats	Land equivalent ratio 1.2; rows of 9–11 m needed to keep 70% of crop yield
Enugu, Nigeria	Tropical savanna	20 kWp (2022)	Elevated 2.65–3.15 m, 20° tilt; mungbean	Orientation reversed the outcome (see below)
Isinya, Kenya	Hot semi-arid	62.1 kWp (2022)	Grid-connected, sized to site demand	Covers 56% of site demand, 97 MWh/yr at full use; leafy crops gained, bulbs and heads lighter

Orientation is not a detail. At Enugu, Nigeria, opaque modules blocked 5–47% of radiation, cut leaf temperature by 3–9% and raised humidity by 3–8%. Under west–east orientation, mungbean grew tall and thin and flowering was delayed by up to ten days; under east–west orientation the improved microclimate produced significantly more pods and seeds and slightly higher seed yield than the unshaded control. Solar generation, however, was higher in the west-facing configuration. Orientation trades energy against agronomy, and that trade must be made deliberately.

OPERATIONAL BENCHMARK: SAGAR, MADHYA PRADESH (INDIA)

A 4.5 MWp PM-KUSUM Component A project on 16 acres of family-owned land, built for INR 18.5 crore (about USD 2.2 million) including a 4.2 km, 11 kV connecting line, financed 70:30 and selling about 8 GWh a year to the state distribution company at INR 3.07 per kWh (about USD 0.037) under a 25-year contract. Elevated structures (3.5 m clearance, 8 m rows, rated for 180 km/h winds) added about 15% to capex, half of it for concrete pillars. A chequered panel pattern lifted wheat to full open-field yield in year two; a 25-million-litre rainwater harvesting system and drip irrigation cut irrigation from four to three times a week.

The lessons are equally practical: persistent utility payment delays strain cash flow; an unbudgeted upgrade of the connecting line cost INR 32 lakh (about USD 39,000); security lighting attracted pests; and panels are cleaned manually by local labour using tractor-mounted mops. Offtaker discipline and interconnection standards matter as much as agronomy.

08 Operations, Maintenance and Risk Management

KEY MESSAGE 08

Operational and maintenance risks are significant, climate-specific and often underestimated

KEY MESSAGE 03

Climatic conditions define the AgriPV value proposition

ASSESSMENT BASIS

M5 O&M comparison and adaptation; M6 Challenge and risk assessment

A well-designed system must also be operated well. Building on the field evidence, this section applies M5 and M6 to show how operation, maintenance and risk differ from conventional solar, and between climatic zones.

Operating an AgriPV system means running a farm and a power plant on the same land. Standard solar maintenance — panel cleaning, vegetation control, inverter, transformer, battery and tracker servicing — must be adapted to crops growing beneath the panels, and each task varies with climate. Four agricultural challenges recur everywhere: **reduced light for photosynthesis**, which cuts growth and yield if unmanaged; **an altered microclimate**, beneficial in dry climates but a cause of fungal disease where humidity rises and airflow falls; **physical obstruction** of machinery, often requiring smaller or specialised equipment; and **uneven water distribution**, as panels intercept rain and leave dry strips beneath and waterlogged strips between rows.

On the electrical side, the Framework highlights dust and the resulting hot-spots on panels; cable damage from sunlight, abrasion and animals; **transformer failure**, which can idle a plant for months because replacements have long lead times; moisture ingress into modules; **ammonia from livestock housing**, which can reduce module output by 10–15% within a few years; and curtailment of output where there is no battery storage (Figure ES 14).

The assessment rated each challenge for likelihood and for impact — separately on electricity generation and on crop production — using published operating experience (studies by the US National Renewable Energy Laboratory and the IEA Photovoltaic Power Systems Program) and stakeholder consultation. Priorities shift sharply by zone. **Extreme temperatures** are high risk in arid and continental zones; **reduced light and uneven terrain** in temperate and continental zones; **humidity, pests and disease and uneven water distribution** in the tropics; and **snow and icing** in continental climates. Transformer failure is a medium risk in dry zones because its impact is severe everywhere, even where it is unlikely. The results are generalised: every site needs its own feasibility-level risk assessment.

Priority Mitigation Measures

For each challenge the Framework sets out climate-specific measures that reduce both likelihood and impact, followed by a check of the remaining (residual) risk (Table ES 10).

Social Dimensions and Community Acceptance

AgriPV sits where energy, agriculture and rural life meet, and its social risks differ from those of conventional solar. Farmers may fear effects on yields, soil and water, and a **loss of autonomy** if leasing hands control to a developer. The complexity of AgriPV may favour large,

Figure ES 14 · Operational risk scores by climatic zone (probability × impact, each scored 1 = low to 3 = high)

	Arid	Semi-arid	Tropical	Temperate	Continental
Extreme temperatures	9	4	1	4	9
Reduced light availability	2	2	4	9	9
Uneven water distribution	1	1	9	4	6
High humidity & precipitation	1	4	9	3	3
Pests and diseases	1	4	9	2	3
Icing and snow	1	1	1	4	9
Uneven terrain	1	1	4	9	9
Dust accumulation	6	6	2	2	2
Transformer failure	6	6	3	3	3
Machinery access limits	4	4	4	4	4
Water quality	4	4	1	1	1
Curtailment (no battery storage)	2	2	2	2	2
Corrosive environment	1	2	3	1	1
Wind and hail	1	2	1	2	3
Data connectivity	2	2	2	2	2
Lack of skilled labour	2	2	2	2	2

How to read

Score = probability × impact, each rated Low 1 · Medium 2 · High 3. Impact is assessed separately for power and for crops.

×	1	2	3
3	3	6	9
2	2	4	6
1	1	2	3

High risk 7–9
Medium 4–6
Low 1–3

Generalised across zones; every site needs its own feasibility-level risk assessment.

Table ES 10 · Priority mitigation measures

Challenge	Principal mitigation measures
Dust and soiling	Soiling sensors to time cleaning; dry brushing or robotic cleaning; windbreaks and optimised tilt; rely on rain cleaning in humid zones but remove bird droppings and pollen promptly
Extreme heat and storms	Toughened glass and dust-resistant coatings; strong mounts and wind barriers; ventilated, dust-proof enclosures for electronics; surge protection against lightning
Reduced light for crops	Use shade deliberately in dry zones (fixed tilt or trackers set to shade at midday); in cool or cloudy zones widen spacing or use vertical bifacial rows that keep the midday sun path open
Uneven water distribution	Drip irrigation to the dry strips under panels; gutters feeding storage tanks; engineered swales or subsurface drainage between rows in wet climates
Humidity, corrosion and water quality	Galvanised or stainless hardware and anti-corrosion coatings; sealed enclosures; inverters raised above flood level; wash panels with soft or demineralised water, not borewell water
Transformer failure	Forced-air or liquid-immersed cooling in hot zones; high-ingress-protection enclosures; moisture breathers with silica gel in humid zones; anti-fouling coatings, wildlife guards and robust earthing
Pests, wildlife and disease	Cable conduits and mesh guards; trimmed vegetation; anti-termite treatment near foundations; ventilation and lower panel density where fungal disease is a risk
Snow, ice, wind and hail	Structures rated for local snow and wind loads; tilt that sheds snow; hail-tested modules; trackers set to safe stow angles during storms
Machinery access	Survey current and future machinery before design; raise clearance; wider post spacing using long-span beams or cable suspension; place foundations outside harvesting paths
Curtailment and skills	Shift irrigation and processing loads into solar peak hours; add battery storage; standard operating procedures, certification and cross-training of farm staff for basic inspections

well-financed operators over smallholders, and benefits may be seen as unfairly shared between developer, landowner, tenant farmer and community. A skills gap — the combination of agronomic and electrical expertise that AgriPV demands — can push work to outside labour and erode local support; and land-use conflicts and complex lease agreements can undermine long-term operation. Clear contracts, transparent revenue sharing, local training and farmercentred ownership models are core mitigation measures, not optional extras.

09 Techno-Economic Viability

KEY MESSAGE 09

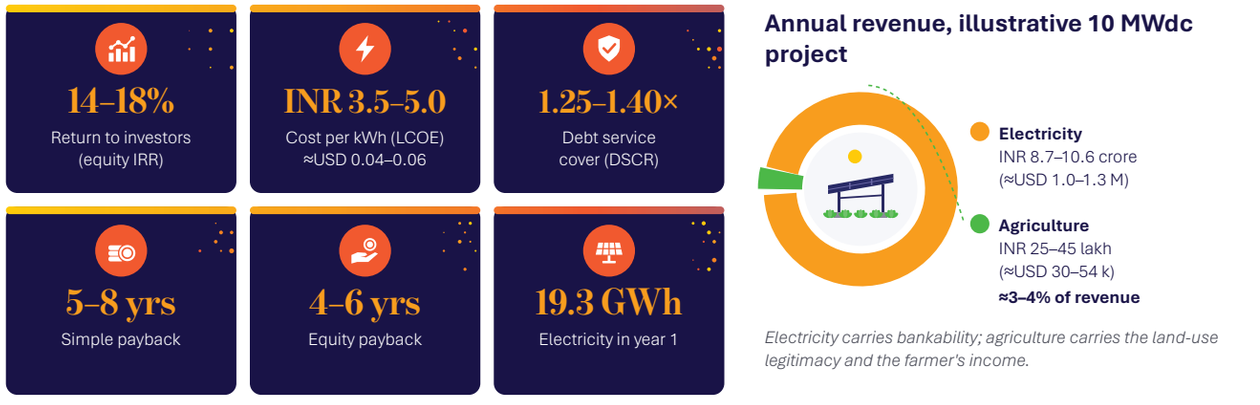
AgriPV is financially viable, but ownership structure determines who benefits

ASSESSMENT BASIS

M7 Techno-commercial assessment

Design, operation and risk all shape cost. Applying M7, this section assesses when AgriPV becomes viable and bankable, using an illustrative project and an explicit set of assumptions.

Figure ES 15 · Illustrative outcomes for a 10 MWdc AgriPV project. IRR = internal rate of return; LCOE = levelised cost of electricity; DSCR = debt service coverage ratio. USD values are indicative at about INR 83 = USD 1. Outcomes are illustrative and vary with site conditions, costs, crops and prices



AgriPV costs more to build than conventional ground-mounted solar because its structures must clear farm machinery and manage light for crops. Taller elevated structures carry the largest premium, and elevated and polyhouse systems cost more than vertical ones; at the operating Sagar project in India the premium was about 15%, and indicative premiums range from about 20% to 50% depending on structure height and design. Operating costs add farm labour, vegetation management, land lease payments where a developer leases from farmers, insurance covering both equipment and crop failure, and administration and compliance monitoring (Figure ES 15).

These ranges rest on an explicit set of assumptions: a 10 MWdc plant; a 25-year life; 12 months of construction; a 22% capacity utilisation factor giving 19.3 GWh in year one; 0.5% annual module degradation; 70% debt and 30% equity, with debt at 9% over ten years; operating and maintenance costs of 1% of capital cost in year one, rising 3–5% a year; tariff escalation of 5% a year; a 14% weighted average cost of capital; two months of receivables; and a 10.5% corporate tax rate. Total

installed cost is taken as INR 5–6 crore per MWdc (about USD 0.6–0.7 million). Net present value at a 10% discount rate is positive. The ranges are indicative, not predictive, and depend on location, project cost and revenue.

Indicative Capital Cost Components

Table ES 11 breaks down the indicative capital cost of the 10 MWdc reference project by component.

Table ES 11 · Indicative capital cost components (10 MWdc reference project)

Component	Indicative value	Component	Indicative value
Solar modules	USD 0.11–0.13 mn / MWdc	Inverters	USD 0.025–0.040 mn / MW
Elevated, vertical or polyhouse structures	USD 0.0018–0.0025 mn / tonne of steel	Cables, combiner boxes and accessories (DC)	USD 0.020–0.035 mn / MWdc
Erection works	USD 0.025–0.045 mn / MWdc	Electrical works (DC and AC)	USD 0.020–0.040 mn / MWdc
Civil works	USD 0.50–1.50 mn	Surveys, studies and engineering	USD 0.20–0.50 mn
Transformers	USD 0.020–0.050 mn / MVA	Switchgear and panels	USD 0.010–0.030 mn / MVA
Monitoring (supervisory control and data acquisition, SCADA), security, fire and safety	USD 0.30–0.80 mn	Drains, roads, fencing and gates	USD 0.30–1.00 mn
Buildings	USD 0.15–0.50 mn	Local area development	USD 0.05–0.30 mn
Overhead line (single circuit)	USD 0.040–0.080 mn / km	Substation bay incl. protection	USD 0.015–0.040 mn / MVA
Contingency	3–5% of engineering, procurement and construction (EPC) cost	Pre-development (permits, approvals)	USD 0.10–0.50 mn

How Costs Change with Climate

Table ES 12 shows how climate changes design, construction, operation and agricultural costs in each zone.

Table ES 12 · How costs change with climate

Zone	Design	Construction	Operations and maintenance	Agriculture
Arid	Water-efficient layout, microclimate modelling, dust-aware spacing	Remote logistics, difficult soils, wind and dust protection	Frequent dust cleaning; heat-related component replacement	Micro-irrigation; heat-and drought-resilient crops
Semi-arid	Balance light for crops with irrigation under variable rainfall	Wind- and hail-resistant structures; integrated irrigation	Periodic cleaning; added pest and disease control	Flexible irrigation; drought-tolerant crops; replanting
Tropical	Drainage, cyclone resistance, crop light management	Soft-soil foundations; cyclone anchoring; monsoon delays	Intensive vegetation control; humidity-related servicing	Heat mitigation, airflow, disease and weed control

Table ES 12 (continued) · How costs change with climate

Zone	Design	Construction	Operations and maintenance	Agriculture
Temperate	Snow, wind and seasonal light; hail and rain protection	Heavier foundations and supports for snow and wind	Snow clearing; crop-yield monitoring and compliance reporting	Low-season light, fungal pressure, vegetation control
Continental	Heavy snow, freeze– thaw cycles, snow-shedding tilt	Cold-rated materials; short winter construction windows	Snow removal; freeze–thaw inspections	Short seasons, frost and summer irrigation needs

Revenue is diversified. Electricity sales — through net metering, sales to distribution companies or direct sales to industrial and commercial buyers — are the largest and most stable stream. Crop sales are the second; partial shade has lifted lettuce and tomato yields by 12– 15% in published studies. Additional income can come from carbon credits (from clean electricity andpotentially from carbon stored in soil), capital subsidies and incentives, and agritourism and education. Keeping lifecycle costs under control depends on climateappropriate engineering, locally adapted farming practice and maintenance planned around each zone's stresses.

10 Business Models and Financing Mechanisms

KEY MESSAGE 09

AgriPV is financially viable, but ownership structure determines who benefits

ASSESSMENT BASIS M7

Techno-commercial assessment

Viability depends not only on costs and revenues but also on who owns the system. Continuing the M7 analysis, this section compares business models and the financing that can make inclusive ownership work (Figure ES 16).

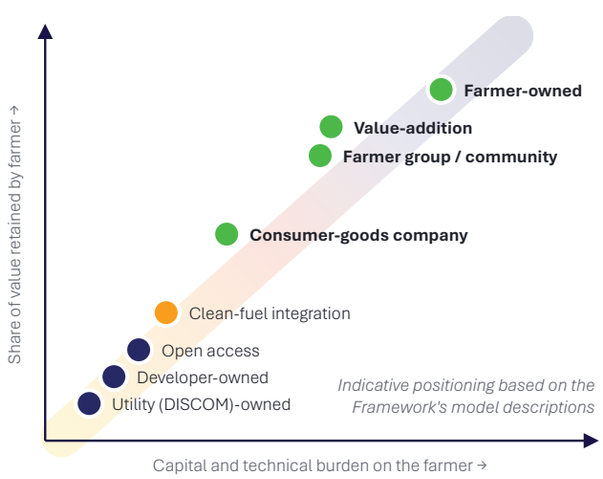
Eight models are assessed. Their suitability depends on landholding size, access to capital, institutional capacity, market linkages and regulation. Models that keep most value on the farm — farmer-owned, FPOowned and value-addition — also place the heaviest capital and skills burden on farmers. Developer, utility and open-access models lower that burden but convert farmers into lessors.

The policy task is to make the inclusive models financeable: aggregate smallholders through farmer producer organisations, pair them with concessional and blended capital, and write revenue-sharing and farming obligations into standard contracts.

Two further families of arrangement are common. In joint ownership, a distribution company and a farmer, or a developer and a farmer, share ownership of the plant and divide electricity and crop revenues by prior agreement; the farmer gains technical support and a lower financial burden, while the partner gains access to land. In revenue-sharing models, ownership stays with one party but income is shared — either as a royalty paid to the landowner (a percentage of electricity revenue or a fixed amount per hectare) or through a profit-sharing agreement covering both energy and farm income. Revenue sharing gives farmers predictable income without upfront investment.

Model	Capital provider	Farmer revenue	Advantage and challenge
Individual farmer-owned	Farmer equity and debt	Crop + electricity sales	Maximum value retention; high capital and technical burden
Farmer producer organisation (FPO) or community-owned	FPO, grants, debt	Profit share + crop sales	Inclusive, shared risk; governance complexity
Developer-owned	Developer	Lease + crop sales	Minimal farmer investment; long lease negotiations
Distribution company (DISCOM)-owned	Utility / public	Lease + crop sales	Grid integration; utility financing and land acquisition
Open access (direct sale to industry)	Private capital	Lease + crop sales	Higher tariffs, diverse buyers; transmission rules
Consumer-goods company (FMCG)-integrated	Mixed	Crops, premium contracts, power benefits	Secured market and traceability; supply-chain alignment
Value addition	Mixed	Processed products + energy savings	Higher farm-gate value; added infrastructure
Clean-fuel integration (e.g. green hydrogen, biogas)	Strategic investors	Crop + biomass revenue	Diversified energy output; technology maturity risk

Figure ES 16 · Business models by farmer value retention and burden (indicative)



Financing Mechanisms and Instruments

AgriPV sits between two capital-intensive sectors, and drawing funds from both is a key enabler. The primary strategy is to integrate support across agriculture, energy, water and finance ministries, so that farm infrastructure grants and loans combine withrenewable-energy funds into one package. Climate funds — the Global Environment Facility, the Least Developed Countries Fund and the Special Climate Change Fund — are natural partners given AgriPV's alignment with climate action, food security and energy access. Instruments range from farmer and developer equity, bank and non-bank lender debt and pooled farmer finance to public utility capital, subsidies and grants, long-term corporate power purchase agreements, blended and impact capital, green bonds and concessional climate finance.

Delivered transactions show the range: Jiangsu Park, China (over 100 MW, developer-owned, backed by a guaranteed feed-in tariff) proved utility-scale bankability with ecotourism; REM TEC, Italy (50–100 MW and above) combined developer equity, institutional investors and project debt; Next2Sun, Germany used equity and commercial debt to keep mechanised farming; Sun'Agri, France blended private, climateinnovation and agricultural finance for dynamic systems; TSE vineyards, France leaned on long-term agricultural contracts; Heggelbach, Germany and Komekurayama, Japan showed cooperative and farmer ownership below 1 MW; and solar cold storage in India used blended finance, subsidies and FPO contributions to cut post-harvest losses.

11 Grid Integration and Deployment Pathways

KEY MESSAGE 10

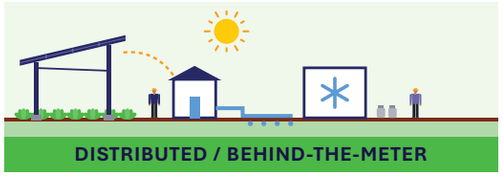
Enabling policy and appropriate deployment pathways are decisive for scale

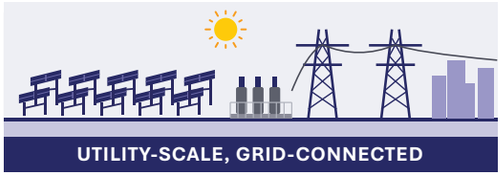
ASSESSMENT BASIS M7

Techno-commercial assessment; M8 Policy and best-practice benchmarking

Revenue from electricity depends on how a project connects to demand. This section completes Part B by comparing distributed and utility-scale pathways, linking the economics of Sections 9 and 10 to the policy agenda in Part C.

Figure ES 17 · Distributed and utility-scale AgriPV compared





	DISTRIBUTED / BEHIND-THE-METER	UTILITY-SCALE, GRID-CONNECTED
Objective	Cut energy cost; secure farm power	Sell electricity to utilities / markets
Typical loads & buyers	Pumps, cold stores, dairy, agro-processing	Long-term power purchase agreements, auctions
Scale	kW to low-MW	Multi-MW to utility scale
Grid dependency	Low to moderate	High — exposed to interconnection delay
Owners & finance	Farmers, producer groups, agribusiness; concessional loans	Independent power producers, utilities; project finance
Policy levers	Net metering / billing, solarisation schemes	Grid planning, transmission, procurement

A grid connection gives a project revenue certainty by allowing it to sell electricity to distribution companies or commercial buyers. But utility-scale and distributed AgriPV are different propositions, with different owners, financiers and policy levers. Distributed systems are sized to local farm loads that coincide with daytime solar output — irrigation, cold storage, milk chilling and food processing — and earn their value from avoided electricity purchases and diesel. Utility-scale systems depend on substation capacity, network reinforcement, connection approvals and curtailment risk (Figure ES 17).

India's **PM-KUSUM** program illustrates how a single scheme can open several pathways at once.

Component A supports grid-connected plants of 500 kW–2 MW, owned by farmers or farmer producer organisations, on barren, fallow, pasture or agricultural land within 5 km of a local 33/11 kV substation — the model used at Sagar. **Component B** supports offgrid solar irrigation pumps, and **Component C** solarises individual grid-connected pumps and entire agricultural feeders. State **net metering and net billing** rules complement these schemes for on-farm uses such as cold storage, pack houses and processing. The program targets 10 GW of decentralised capacity, 1.4 million stand-alone solar pumps and 3.5 million gridconnected pumps.

RECOMMENDED NEAR -TERM DEPLOYMENT PATH WAY

For many ISA member countries, distributed and behind-the-meter AgriPV is the more practical near-term pathway, especially where rural networks are weak or connection queues are long. Matching generation to irrigation, cold storage and processing loads improves farm energy security and cuts costs without waiting for transmission.

Utility-scale AgriPV remains essential for national targets, but its success depends on grid readiness. Site selection must add substation proximity, available capacity and interconnection timelines to solar resource and agricultural suitability.

PART C

From Findings to Action



Part C turns the findings into action. It reviews international policy experience (Section 12), summarises what the Framework delivers (Section 13), sets out recommendations for ISA member countries (Section 14), and explains how to apply the toolkit and the limits of the analysis (Section 15).

12 International Policy Benchmarks

KEY MESSAGE 10

Enabling policy and appropriate deployment pathways are decisive for scale

ASSESSMENT BASIS

M8 Policy and best-practice benchmarking

The findings in Part B show that enabling conditions are decisive. Applying M8 to eight benchmark markets, this section identifies the policy pillars and best practices behind successful deployment.

Benchmarking of France, Germany, Italy, Japan, India, Kenya, Australia and the United States points to a consistent conclusion. **Regulatory certainty is the strongest enabler**: clear rules on dual land use, agricultural compliance and permitting give developers and investors confidence. **Financial incentives remain the primary catalyst**, through feed-in tariffs, grants, tax relief and concessional finance. **National strategies are moving from pilots to commercialisation**, positioning AgriPV to serve energy, agricultural resilience and rural income together. And **ecosystem support** — R&D, standards, monitoring and capacity building — increasingly distinguishes fast-moving markets (Figure ES 18).

The seven best practices identified in the benchmarked markets are summarised below. Rather than ranking countries, the table sets out what ISA member countries need to put in place to adapt each practice to their own context, with illustrative examples (Table ES 13).

Figure ES 18 · The four complementary policy pillars



Table ES 13 · Best practices and what countries need to put in place

Best practice	What it involves	What countries need to put in place	Illustrative examples
Regulatory clarity for dual-use land	Legal definition of AgriPV, eligibility criteria and permitting rules that keep farming the primary land use	Adopt a legal definition of AgriPV and a simple dual-use test suited to local farming systems; keep the land's agricultural status; publish clear permitting steps.	France's dedicated AgriPV framework (2024); Japan's Solar Sharing model, which requires continued farming
Distributed generation and grid integration	Self-consumption, net metering and net billing that reduce reliance on grid expansion	Enable net metering or net billing for small AgriPV plants; reserve feeder and substation capacity; simplify connection procedures for farmer-scale projects.	India's PM-KUSUM (500 kW–2 MW plants); Kenya's Net Metering Regulations
Agricultural solarisation programs	Dedicated schemes for irrigation pumping, agricultural feeders and cold storage	Link AgriPV to existing solar-pump, irrigation, feeder and cold-chain programmes rather than creating parallel schemes.	PM-KUSUM targets of 10 GW decentralised capacity and millions of solar pumps
Financial incentives	Feed-in tariffs, auctions, grants, tax relief and concessional finance	Tie support to genuine dual use, such as yield and coverage conditions; choose tariffs or tenders suited to market maturity; add concessional finance for farmer-owned models.	Japan's feed-in tariff; Italy's national AgriPV tenders; European incentive schemes
Agricultural productivity safeguards	Required continued cultivation, yield monitoring and periodic compliance checks	Set measurable thresholds for continued farming or yield, with simple monitoring against control plots and periodic compliance reporting.	Japan's periodic yield reviews; France's requirement to demonstrate agricultural benefit
National policy alignment	AgriPV written into energy transition plans, renewable targets and land-use planning	Include AgriPV in renewable energy targets and in agricultural and land-use plans, with a joint focal point across energy and agriculture ministries.	France's Multi-Year Energy Plan; Germany's Renewable Energy Sources Act (EEG) special status; Japan's Green Growth Strategy
Research, pilots and capacity building	Public R&D, demonstration projects, standards, monitoring and farmer training	Start with monitored pilots in each climate zone, publish the results openly, and train farmers, installers and extension services.	US National Renewable Energy Laboratory and Department of Energy guidance and databases; virtual power plant aggregation in the EU, Australia and Japan

13 What the Framework Delivers and What It Enables

KEY MESSAGE 01

AgriPV has matured into an established solution to the land–energy challenge

KEY MESSAGE 07

The Land Equivalent Ratio is the benchmark of genuine dual use

KEY MESSAGE 09

AgriPV is financially viable, but ownership structure determines who benefits

KEY MESSAGE 10

Enabling policy and appropriate deployment pathways are decisive for scale

Drawing Parts A and B together, this section lists the practical instruments the study has produced and the outcomes they make possible.

The assessment has produced a set of practical instruments rather than a single report. Each can be used on its own, and together they support the full journey from screening a site to designing a national programme.

Outputs of the Study

Table ES 14 lists the outputs of the study, what each contains and who it is for.

Table ES 14 · Outputs of the study

Output	What it contains	Primary users
Global Agriphotovoltaics Climate-Zone Technical Framework	Six chapters covering design fundamentals, zone toolkits, operations and grid access, economics and financing, and recommendations, with six technical appendices	All stakeholders
Five climate-zone toolkits	For arid, semi-arid, tropical, temperate and continental zones: site conditions, crop priorities, configurations, O&M practice, risks and mitigation	Planners, developers, extension services
Site suitability method	Six-step assessment, five-category minimum data pack and remote screening workflow with confidence rating	Developers, agriculture and energy departments
Crop selection method	Four-step process, Go/No-Go gate, eight-criterion weighted scoring matrix and shade-tolerance review of 12 crop groups	Agronomists, farmer organisations, developers
Design guidance	Configuration assessment, design parameter matrix, reference design and simulated yields, technology options and safety standards	Designers and engineers
Risk and mitigation framework	Probability-and-impact scoring of 16 operational challenges across five zones, with climate-specific mitigation measures	Operators, lenders, insurers
Techno-commercial framework	Capital and operating cost components, assumption set, financial metrics, eight business models, revenue-sharing options and eight financing cases	Financiers, investors, ministries

Table ES 14 (continued) · Outputs of the study

Output	What it contains	Primary users
Policy benchmark	Review of eight markets, four policy pillars and seven best practices with country examples	Ministers, regulators, ISA National Focal Points
Evidence library and demonstrations	Eight documented projects, site visits to operating plants and four worked site demonstrations in Egypt, India and Germany	All stakeholders; capacity building
Digital AgriPV Site Screener (prototype)	Interactive tool applying the Framework's zone, crop, design, risk and viability logic to a site, producing a one-page brief	Under development for testing with member countries

What Member Countries Can Achieve

Applied systematically, the Framework allows countries to pursue six outcomes. Each is grounded in the evidence assembled in this study, and each depends on specific enabling conditions (Table ES 15).

Table ES 15 · What member countries can achieve

Outcome	Evidence from the Framework	What it requires
Expand solar capacity without losing farmland	Documented land equivalent ratios of 1.2–1.65: shared land outperforms separate uses	A legal definition of AgriPV and a dual-use test for incentives (Sections 7, 12, 14)
Save water and strengthen climate resilience	Water savings of 15–30% in dry climates; 25– 30% for wheat at Sagar; protection from heat, hail, frost and heavy rain	Climate-matched design and crop selection (Sections 4–6)
Raise and diversify farm incomes	A second income stream; high-value crops such as medicinal plants, ginger and flowers ranking highest in demonstrations; value-addition models	Inclusive ownership, revenue-sharing contracts and market linkages (Section 10)
Extend reliable energy to rural economies	Behind-the-meter systems for irrigation, cold storage and processing; India's PM-KUSUM as a multi-pathway model	Net metering, feeder programmes and grid planning (Section 11)
Mobilise private and climate finance	Viable under illustrative assumptions, with site-specific returns; delivered transactions in China, Europe, Japan and India	Blended facilities, bankable contracts and reliable offtakers (Sections 9–10)
Build a credible national project pipeline	Screening method, data pack, crop and design methods validated at four real sites	Capacity building, monitored pilots and open performance data (Sections 14–15)

HOW THE INSTRUMENTS FIT TOGETHER

The Framework sets the method; the zone toolkits and the screening tool apply it to specific sites; monitored pilots generate local evidence; and that evidence informs national rules, incentives and procurement. ISA's role is to support member countries at each step and to refine the Framework as field experience grows.

14 Recommendations for ISA Member Countries

KEY MESSAGE 07

The Land Equivalent Ratio is the benchmark of genuine dual use

KEY MESSAGE 09

AgriPV is financially viable, but ownership structure determines who benefits

KEY MESSAGE 10

Enabling policy and appropriate deployment pathways are decisive for scale

Building on the policy benchmarks and the study's outputs, this section translates the findings into a coherent agenda for each group of stakeholders.

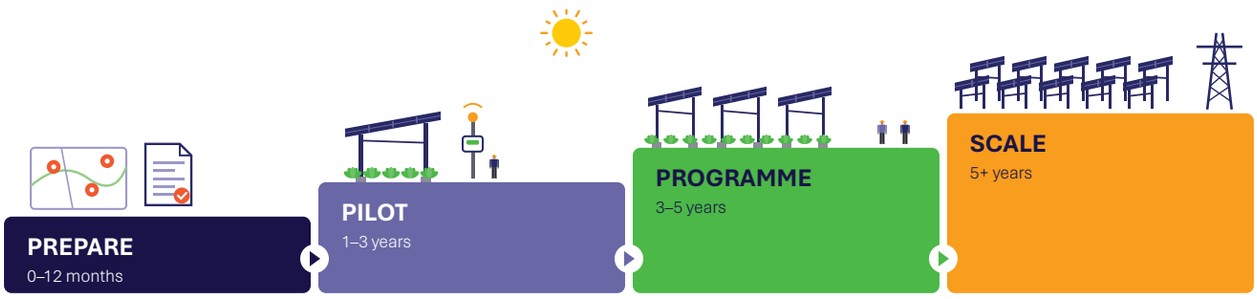
The Framework's findings translate into a coherent agenda for each stakeholder group. The actions below synthesise the evidence and policy benchmarks presented in this summary; countries should adapt them to their own land-use, tariff and institutional regimes (Table ES 16).

Table ES 16 · Recommendations by stakeholder

Stakeholder	Priority actions
Ministers and ISA National Focal Points	Adopt AgriPV as a joint energy–agriculture priority with a named inter-ministerial lead; set an indicative national ambition; mandate pooled use of farm, energy, water and climate budgets.
Regulators and land authorities	Legislate a definition of AgriPV with a dual-use test (for example LER > 1 and minimum agricultural output); keep farming as the primary land use; streamline permits and require periodic yield monitoring.
Utilities and distribution companies	Open feeder-level and behind-the-meter windows; publish hosting capacity near farm clusters; set clear interconnection standards up front; guarantee timely payment to small generators.
Financiers and development partners	Build blended facilities that pair concessional and climate finance with commercial debt; accept aggregation of smallholders through farmer producer organisations; recognise crop and energy revenues together in credit appraisal.
Developers, farmer organisations and farmers	Apply the four-step crop method and six-step site assessment before engineering; choose configuration by zone; budget climate-specific O&M; agree transparent revenue-sharing and farming obligations.
ISA Secretariat	Support country pilots in every zone present; host an open AgriPV performance database; run capacity building for officials, installers and farmers; refresh this Framework as evidence grows.

Sequencing matters as much as content. Countries move most safely from pilots to large-scale, bankable programmes by building rules and evidence first, then scaling finance and procurement on what the evidence shows (Figure ES 19).

Figure ES 19 · An indicative pathway from preparation to scale



- Adopt a legal AgriPV definition and a land-use efficiency test
- Map zones and priority districts with the Framework toolkit
- Name a joint energy–agriculture focal point
- Fund monitored pilots in each climatic zone present
- Publish yield, water and energy data openly
- Test 2–3 ownership models, incl. FPO-led
- Launch a dedicated tender or solarisation window
- Blend climate finance with farm and energy budgets
- Standardize O&M and compliance monitoring
- Embed AgriPV in national energy and land-use plans
- Move to bankable, market-led procurement
- Refresh guidance as field evidence matures

15 Application of the Toolkit and Limitations of the Framework

Finally, this section explains how the toolkit applies the Framework's method in practice, and the limitations that govern how its results should be interpreted.

The **AgriPV Toolkit** (Chapter 3 of the Framework) applies the same sequence to each climatic zone: understand the site conditions; select crops and define the agricultural practices; choose the system configuration; compare operations and maintenance with conventional solar; identify environmental challenges; assess their risk; and set mitigation measures. It is a decision-support resource for screening and pre-feasibility that structures assessment of site conditions, crop suitability, climate-specific design, operational requirements and economic drivers, and gives agricultural, energy, financial and policy stakeholders a common language. Its outputs should inform preliminary decisions, prioritise sites and design options for detailed evaluation, and identify information gaps. They are **not definitive recommendations for implementation**: local agronomic validation, engineering, regulatory review, environmental and social assessment and investment-grade financial analysis all remain essential.

Six limitations govern interpretation. **Context-specific applicability**: guidance must be adapted to soil, water, farm size, tenure and practice, not replicated. **Local data**: field-level evidence on shade response, microclimate, yield and long-term O&M cost remains limited in many regions. **Changing technology**: advances in semi-transparent modules, tracking, digital agriculture and precision irrigation will shift trade-offs, so guidance should be updated periodically. **Policy variability**: national rules on land classification, subsidies, evacuation, tariffs and approvals are outside scope. **Market sensitivity**: returns depend on crop prices, input costs, tariffs, financing and climate risk. **No substitute for specialists**: projects need qualified engineers and agronomists.

Structure of the Full Framework

Table ES 17 shows how the full Framework is organised and who each chapter is written for.



Table ES 17 · Structure of the full Framework

Chapter	What it contains	Written for
1 **Introduction and approach**	Rationale, objectives, approach, Köppen–Geiger basis, limitations	All readers
2 **Global AgriPV Success Stories and Implementation Insights**	Global case studies across climatic zones, project configurations, crop performance, energy generation, implementation models, stakeholder insights, success factors and transferable lessons	Policymakers, planners, project developers, practitioners and financiers
3 **Design fundamentals**	Key concepts, configurations, shade tolerance, PV sizing, bifacial gain, innovative modules, safety and standards	Planners, designers, developers
4 **Toolkit across climatic zones**	Zone context, crop priorities, configurations, O&M practice, risk and mitigation	Practitioners, policymakers, financiers
5 **O&M and grid connectivity**	O&M comparison, risk assessment, distributed and utility-scale pathways	Developers, utilities, regulators
6 **Economics and financing**	Capex and opex, financial metrics, revenue, business models, financing cases	Financiers, investors, planners
7 **Findings and recommendations**	Cross-zone comparison, transferable principles, policy recommendations, toolkit use	Decision-makers, programme designers
Appendices A–E	Consultation register, Köppen–Geiger detail, mitigation matrix, four worked demonstrations, case studies, cost assumptions	Technical teams, analysts

CONCLUDING OBSERVATIONS

Applied with care, AgriPV lets countries grow clean power without shrinking their farmland — and often makes that farmland more resilient to heat, drought and extreme weather. The conditions for success are clear: put agriculture first in design, choose crops and configurations by climate, price operations honestly, share value fairly with farmers, and build the four policy pillars. This Framework is designed to be refined as field experience expands, so that ISA member countries can move from pilots to large-scale, bankable AgriPV programmes with confidence.



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List of abbreviations

Abbreviation	Full Form
AgriPV/APV	Agriphotovoltaics
BESS	Battery Energy Storage System
C3	C3 Photosynthetic Pathway (plant physiology)
C4	C4 Photosynthetic Pathway (plant physiology)
CAPEX	Capital Expenditure
CIAL	Cochin International Airport Limited
Discom	Distribution Company
DRE	Decentralized Renewable Energy
EPC	Engineering, Procurement, and Construction
FPOs	Farmer Producer Organizations
FYM	Farmyard Manure
GCF	Green Climate Fund
GCR	Ground Coverage Ratio
GDD	Growing Degree Days
GI	Galvanized Iron
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
INM	Integrated Nutrient Management
IPM	Integrated Pest Management
IPP	Independent Power Producer
ISA	International Solar Alliance
JV	Joint Venture
JVVNL	Jaipur Vidyut Vitran Nigam Limited
kW	Kilowatt

kWp	Kilowatt peak
LCoE	Levelized Cost of Electricity
LER	Land Equivalent Ratio
LSP	Light Saturation Point
MPNRED	Madhya Pradesh New and Renewable Energy Department
MSP	Minimum Support Price
MW	Megawatt
MWp	Megawatt peak
O&M	Operations and Maintenance
OEM	Original Equipment Manufacturer
OPEX	Operational Expenditure
PAR	Photosynthetically Active Radiation
PJTSAU	Professor Jayashankar Telangana State Agricultural University
PMFBY	Pradhan Mantri Fasal Bima Yojana (Crop Insurance Scheme, India)
PPA	Power Purchase Agreement
PV	Photovoltaic
PwC	PricewaterhouseCoopers
SDI	Subsurface Drip Irrigation
SoH	State of Health (battery health metric)
STAAD	Structural Analysis and Design
STU	State Transmission Utility

Crop names and their scientific names used in the report

Crop name (common/regional)	Scientific name
Asparagus	Asparagus officinalis
Banana	Musa spp.
Barley	Hordeum vulgare
Beet / Beetroot	Beta vulgaris
Berries (generic)	Various spp. (Fragaria, Rubus, Vaccinium etc.)
Black pepper	Piper nigrum
Brassicas (crop group)	Brassica spp.
Carrot	Daucus carota subsp. sativus
Cassava	Manihot esculenta
Chickpea	Cicer arietinum
Chives	Allium schoenoprasum
Cilantro / Coriander	Coriandrum sativum
Clover	Trifolium spp.
Cocoa/Cacao	Theobroma cacao
Coffee	Coffea arabica / Coffea spp.
Cotton	Gossypium spp.
Date palm	Phoenix dactylifera
Forages	Various forage species
Fruit trees (generic)	Various species
Ginger	Zingiber officinale
Gram	Cicer arietinum
Grapes	Vitis vinifera
Herbs (generic)	Various species
Kale	Brassica oleracea var. sabellica

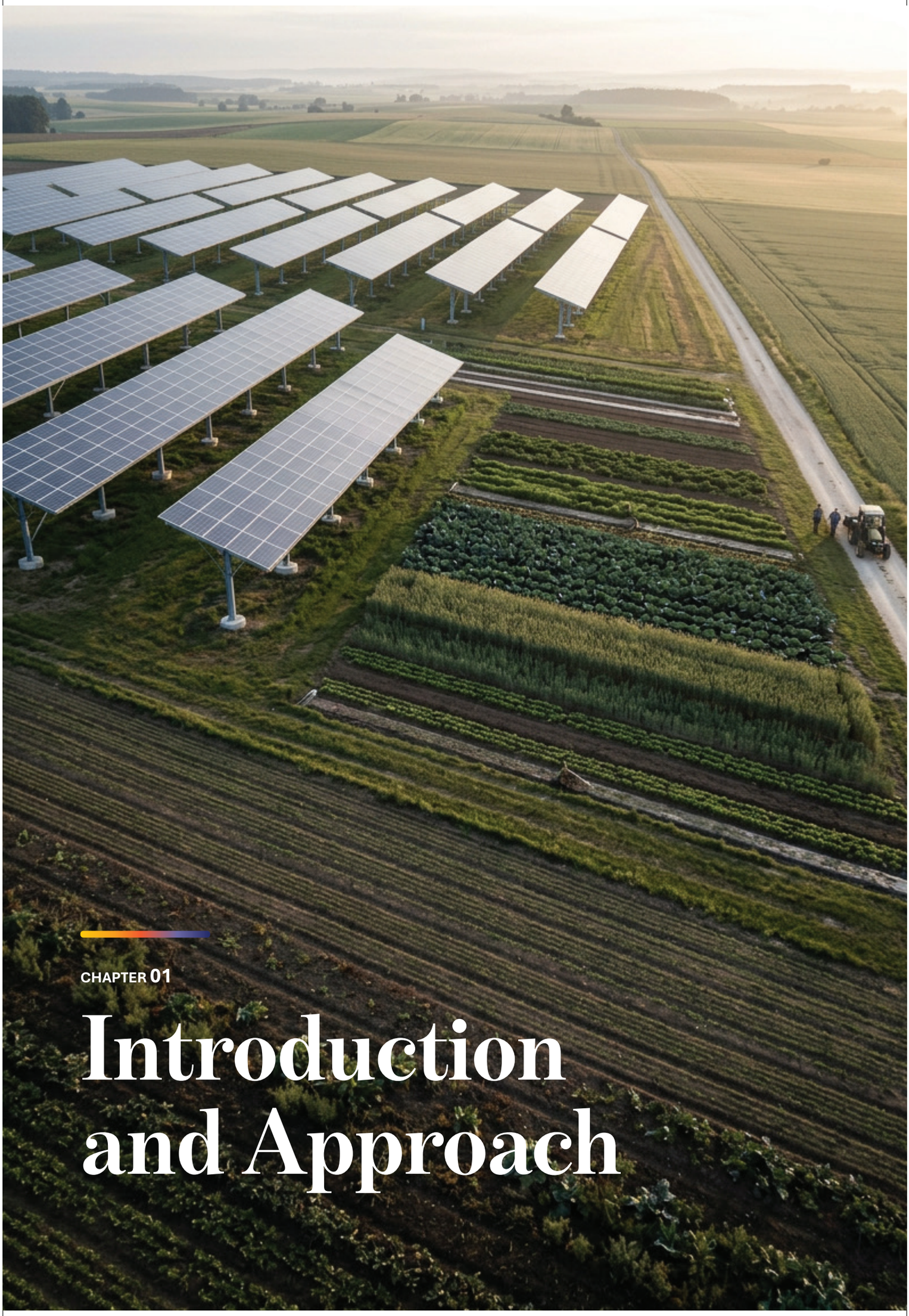
Leafy vegetables / leafy greens	Various species
Legumes (generic)	Fabaceae family
Lettuce	Lactuca sativa
Maize / Corn	Zea mays
Millet (generic)	Pennisetum glaucum and other millet species
Mint	Mentha spp.
Mustard	Brassica juncea
Palm oil crop (Oil palm)	Elaeis guineensis
Peppers	Capsicum annuum
Potato	Solanum tuberosum
Radish	Raphanus sativus
Root crops	Various species
Rye	Secale cereale
Sorghum	Sorghum bicolor
Soy / Soybean	Glycine max
Spices (generic)	Various species
Spinach	Spinacia oleracea
Strawberry	Fragaria × ananassa
Sugarcane	Saccharum officinarum
Sweet potato	Ipomoea batatas
Tomato	Solanum lycopersicum
Turmeric	Curcuma longa
Vanilla	Vanilla planifolia
Vetch	Vicia spp.
Wheat	Triticum aestivum

How to Navigate this Framework

This guideline has been structured as a progressive, decision oriented document, allowing different stakeholder groups to quickly access the sections most relevant to their roles while maintaining a coherent end to end narrative from concept to implementation.

- **Chapter 1 – Introduction** Provides the context for the study, outlining the rationale for Agriphotovoltaics, the objectives of the guideline, the study approach, and guidance on how to navigate the guideline. This chapter sets the strategic framing and intended use of the guidelines.
- **Chapter 2 - Global AgriPV Success Stories and Implementation Insights**, reviews selected AgriPV projects across different countries and climatic zones to draw practical lessons on system design, crop performance, energy generation, water management, and operational challenges. The chapter highlights how site conditions, crop characteristics, panel configuration, and farming practices influence project outcomes, providing an evidence base for the technical framework and design guidance developed in subsequent chapters.
- **Chapter 3 – Agriphotovoltaics System Design and Configuration** Presents the core technical and agricultural foundation of the guideline. This chapter introduces key Agriphotovoltaics concepts and terminologies, evaluates major system configurations (elevated, vertical, and polyhouse Agriphotovoltaics), and discusses crop driven design considerations. It also covers site assessment, structural design parameters, PV system sizing, innovative PV technologies, and integration of agricultural and solar components. This chapter is intended as a reference for planners, designers, and developers.
- **Chapter 4 – Toolkit for Agriphotovoltaics Development Across Climatic Zones** Translates the design principles into climate specific, action oriented toolkits for five climatic zones: arid/semi arid, tropical, temperate, continental, and others where relevant. For each zone, the chapter outlines environmental context, crop selection priorities, preferred system configurations, key agricultural and O&M practices, risk assessment, mitigation strategies, and illustrative case insights. This chapter is designed for practitioners, policymakers, and financiers seeking implementation ready guidance.
- **Chapter 5 – Key considerations for O&M and grid connectivity of AgriPV projects:** This chapter guides readers through the practical requirements for project deployment, including operations and maintenance considerations, grid connectivity options, distributed and behind-the-meter models, and the broader institutional and regulatory conditions needed for implementation.
- **Chapter 6 – Economics & Financing:** This chapter enables readers to assess the parameters for commercial viability of an AgriPV project by outlining key capital and operating cost components, relevant financial metrics, potential revenue streams, and suitable business and ownership models.
- **Chapter 7 – Key Findings & Recommendations:** This chapter consolidates the principal insights from the guideline through cross-climatic-zone comparisons, transferable design principles, and actionable recommendations to support ISA member countries and other stakeholders in planning and scaling context-appropriate AgriPV program.
- **Annexures –** Detailed tables, figures, and illustrative case examples are embedded throughout the guideline to support clarity and practical application. These elements provide quick reference points for comparative assessment, design tradeoffs, and operational considerations.

Overall, the guideline is designed to function both as a strategic reference document for policy and program design and as a practical toolkit to support feasibility assessment, project development, and scalable deployment of AgriPV across ISA member countries.



CHAPTER 01

Introduction and Approach

1.1 Background & History of the AgriPV system

Agriphotovoltaics (AgriPV) is an approach that combines solar photovoltaic electricity generation with agricultural activities on the same land. The idea of co-locating photovoltaics and agriculture was first suggested in 1981 by Adolf Goetzberger and Armin Zastrow[1]. This system involves installing solar panels above or between crops, or on structures like greenhouses/polyhouses, to simultaneously generate electricity and support farming. This dual-use strategy maximizes the utility of agricultural land, enabling the simultaneous cultivation of crops and generation of renewable energy.

Depending on system configuration and local conditions, solar PV structures can modify the crop microclimate by influencing solar radiation, temperature, wind exposure, and soil moisture. These effects can provide benefits such as reduced heat stress and water loss for suitable crops, while the co-location of agriculture and solar generation can also create opportunities for diversified farm income.

AgriPV installations have been developed in countries including China, India, Vietnam, Thailand, Kazakhstan, Malaysia, Austria, France, Germany, Italy, the Netherlands, and Chile, among others. Global AgriPV capacity has expanded rapidly, increasing from approximately 5 MWp in 2012 to more than 14 GWp by 2021[2] and about 18.4 GW by mid-2025[3]. Policy support and enabling incentive frameworks in countries such as Japan, China, France, the United States, Germany, and the Republic of Korea have contributed to the expansion of AgriPV deployment.

Against this background, ISA has undertaken a study to assess the suitability of AgriPV across five priority climatic zones within selected regions and countries, identify appropriate crop types and cropping patterns, and examine technical configurations suited to different climatic and agricultural conditions. The assessment also considers how system configurations can influence crop microclimates and how climate-specific design and operational challenges can be addressed.

1.2 Scope of the study

The primary objective of this study is to develop a comprehensive, climate-responsive technical framework for the systematic planning, design, and implementation of AgriPV across diverse climatic zones. The framework is intended to support informed decision-making by policymakers, project developers, farmers, financiers, and other stakeholders by integrating agricultural requirements with solar PV system design.

To achieve this objective, the study brings together five complementary areas of analysis, moving from climate-specific priorities and agricultural requirements to system configuration, crop selection, and operational considerations:

Specifically, the study aims to:

- **Provide climate-specific guidance:** Develop differentiated AgriPV design and operational guidance across five priority climatic zones, arid, semi-arid, tropical, temperate, and continental using the Köppen–Geiger climatic classification as the analytical foundation.
- **Place agriculture at the core of system design:** Establish agricultural productivity as the primary design driver by linking crop characteristics, shade tolerance, water requirements, soil and land type and farming practices with solar PV structural and layout decisions.

1 Goetzberger, A., & Zastrow, A. (1981). On the coexistence of solar-energy conversion and plant cultivation. International Journal of Solar Energy, 1(1), 55-69
2 Agri-Photovoltaics Potential in India: Pathways for Sustainable Energy–Food Solutions, https://teriin.org/sites/default/files/files/Agriphotovoltaics-Potential-in-India.pdf
3 Agriphotovoltaics In 2025: Scaling Food And Solar Together

- **Evaluate AgriPV system configurations:** Assess the technical suitability, benefits, tradeoffs, and application contexts of key AgriPV configurations including elevated, vertical, and polyhouse AgriPV across different climatic zones and cropping systems.
- **Support crop selection and prioritization:** Introduce a structured, transparent crop selection and prioritization methodology that enables stakeholders to identify crops that are agronomically viable, operationally compatible, and economically attractive under partial shading conditions.
- **Identify operational challenges and mitigation measures:** Systematically assess climate-specific operational and maintenance challenges affecting both agricultural activities and solar PV systems, and recommend targeted mitigation strategies to enhance system reliability, resilience, and long-term performance.

Taken together, these objectives are intended to position AgriPV not as a niche or experimental solution, but as a **scalable, integrated land-use strategy** that can simultaneously advance renewable energy deployment, agricultural productivity, farmer livelihoods, water security, and climate resilience across ISA member countries.

1.3 Use of Köppen-Geiger climate classification system

The objectives outlined above require a consistent basis for differentiating AgriPV considerations across geographical and climatic contexts. Climate is particularly important because it influences crop suitability, water requirements, shading needs, structural conditions, agricultural operations, and system performance. To establish a common analytical basis for comparing these conditions across different regions, the study uses the Köppen-Geiger climate classification system as the starting point for its climate-zone assessment.

Using this classification as the analytical foundation, the framework adopts a structured, modular, and climate led approach that is technically robust, agriculturally grounded, and operationally deployable across ISA Member Countries. The approach has been designed to move systematically from context definition to design guidance and finally to implementation-oriented insights, with agriculture positioned as the primary system driver throughout. At the core of the approach is the recognition that AgriPV outcomes are highly context-specific and must be tailored to local climatic conditions, cropping systems, and operational constraints. Accordingly, the study is organized around five priority climatic zones—arid, semi-arid, tropical, temperate, and continental—using the Köppen–Geiger climatic classification to ensure global applicability and scientific consistency.

Climate-led structuring and agricultural prioritization

The first step of the approach involves classifying project contexts by climatic zone and establishing the **strategic agricultural objective for each zone (e.g., water conservation in arid zones**, heat stress reduction in tropical zones, season extension in temperate zones). This climate led lens sets the foundation for all subsequent design, crop selection, and operational decisions and ensures that AgriPV systems are responsive to local agro climatic realities rather than driven solely by energy optimization considerations. This establishes the climatic context within which subsequent crop selection and system design decisions are assessed.

Agricultural requirements—such as crop height, shade tolerance, water needs, mechanization compatibility, and farming practices—are treated as the **primary design constraints**, with solar PV system parameters optimized within these boundaries. This approach represents a deliberate shift from conventional solar-centric planning toward a truly integrated land-use perspective.

Within this climate-led structure, the assessment translates climatic and agricultural conditions into three interconnected areas:

- **Köppen-Geiger climatic classification and corresponding crop suitability**
- **Technical design considerations required for setting up an AgriPV system**
- **Operational challenges likely to arise and strategies to effectively mitigate them**

Together, these components connect the climate assessment with crop selection, technical system design, and operational planning. They are developed throughout the report, with climate-specific considerations and expected outcomes identified for each priority climatic zone.

The Köppen-Geiger climate classification system is a widely used framework for classifying global climate patterns based primarily on temperature and precipitation, with the classification reflecting climatic conditions relevant to vegetation. The system comprises five principal climate groups: Tropical (A), Dry (B), Temperate (C), Continental or Boreal (D), and Polar (E), which are further divided into subtypes based on temperature and precipitation characteristics. The classification provides a consistent basis for differentiating climatic contexts across regions and is therefore used in this framework as the foundation for the climate-zone assessment.

For the purposes of this AgriPV assessment, the broader Köppen-Geiger classification is organized into five priority climatic contexts: tropical, arid, semi-arid, temperate, and continental. Arid and semi-arid conditions are considered separately because their agricultural constraints, water availability, and potential AgriPV responses can differ substantially despite both falling within the broader Dry (B) climate group. The Polar group is retained in the broader classification for completeness but is not included in the detailed AgriPV assessment because of its limited relevance to conventional open-field agricultural production. The global distribution of the Köppen-Geiger climate classes is shown in Figure 1.

Figure 1: Köppen-Geiger classification system[4]

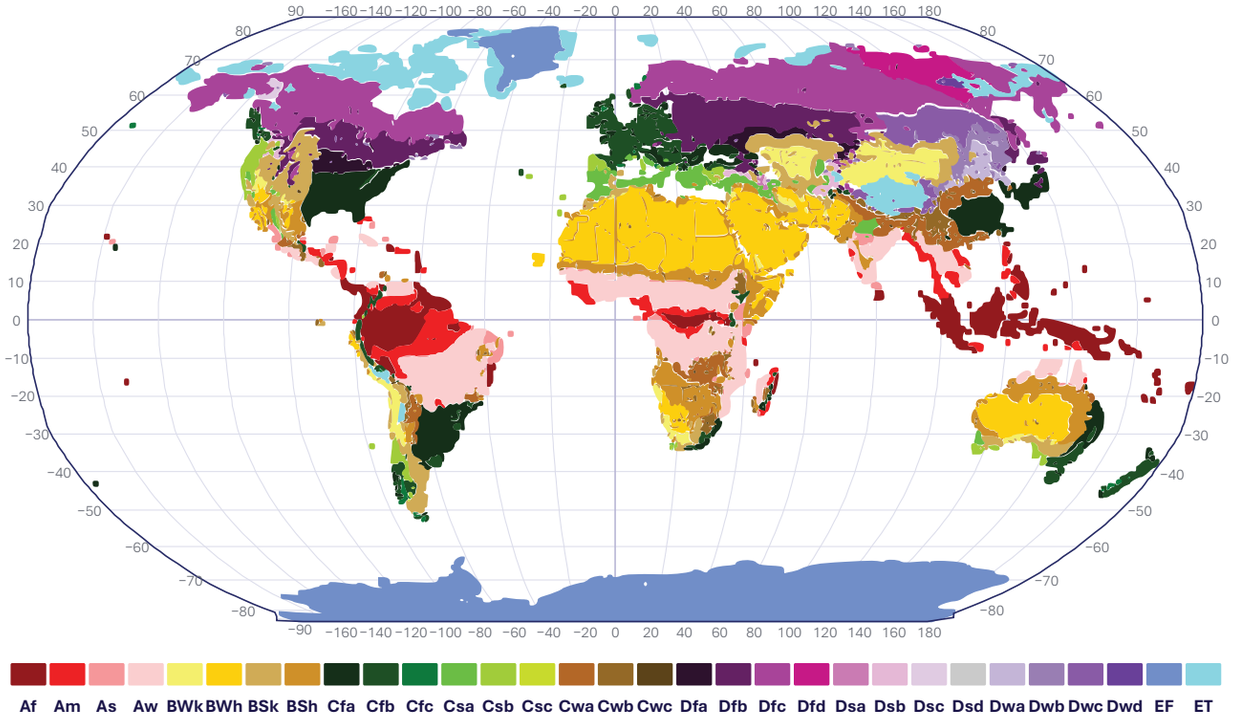


Figure 1 illustrates the global distribution of the major Köppen-Geiger climate groups and highlights the considerable climatic diversity across regions where agricultural activities and AgriPV deployment may occur. The principal climate groups differ in their temperature, precipitation, seasonality, and moisture

4 Beck, H., Zimmermann, N., McVicar, T. et al. Present and future Köppen-Geiger climate classification maps at 1-km resolution. Sci Data 5, 180214 (2018). https://doi.org/10.1038/sdata.2018.214 Image https://www.noaa.gov/jetstream/global/climate-zones/jetstream-max-addition-k-ppen-geiger-climate-subdivisions

conditions, which in turn influence agricultural practices, crop suitability, water availability, and the technical and operational requirements of AgriPV systems. The key characteristics of these climate groups are briefly described below.

- **Tropical Climates (A):** The tropical climate group, or Zone A, generally spans the equatorial and near-equatorial regions between the Tropic of Cancer (23.5°N) and the Tropic of Capricorn (23.5°S), including large parts of Central Africa, the Amazon Basin, and Southeast Asia. It is characterized by high temperatures throughout the year, with limited seasonal temperature variation. The different tropical subtypes vary considerably in their precipitation patterns, ranging from consistently wet conditions to pronounced wet and dry seasons. High humidity, intense solar radiation, and substantial rainfall can strongly influence crop selection, soil-water conditions, agricultural operations, and PV system performance. Crops such as banana, cocoa, and coffee are commonly cultivated in tropical regions. From an AgriPV perspective, these conditions make considerations such as rainfall management, crop shading, humidity, ventilation, soil moisture, drainage, and structural resilience particularly relevant.

- **Dry Climates (B):** Zone B encompasses arid and semi-arid regions where potential evapotranspiration generally exceeds precipitation, resulting in water-limited conditions. These climates commonly occur in subtropical regions and continental interiors and account for a substantial proportion of the world's land area. Annual precipitation is generally low, although conditions vary considerably between arid and semi-arid environments. Arid areas may receive less than 250 mm of annual precipitation, while semi-arid areas generally receive higher but still seasonally limited rainfall. High evaporative demand, water scarcity, drought conditions, and substantial diurnal or seasonal temperature variation can constrain agricultural production. Agriculture in these regions often depends on irrigation and water-efficient practices, while technologies such as drip irrigation can improve water-use efficiency. Crops and agricultural systems in dry climates therefore require careful consideration of water availability, crop water requirements, shading, soil moisture, and temperature conditions. For AgriPV, these characteristics make water conservation, microclimate moderation, and appropriate PV array configuration particularly important considerations.

- **Temperate Climates (C):** The temperate climate group, or Zone C, generally occurs between the tropical and higher-latitude climate regions, broadly spanning parts of North America, Europe, and Asia. It is characterized by moderate temperatures and pronounced seasonal variation, with conditions ranging from relatively mild winters to warm summers depending on the subtype. Precipitation varies considerably across temperate regions, with annual rainfall in many areas falling within approximately 500–1,500 mm, although substantial local variation exists. The combination of seasonal temperature, rainfall, and growing-period characteristics supports a wide range of agricultural systems and crops. However, droughts, floods, heat events, and other forms of weather variability can affect agricultural productivity. For AgriPV, seasonal crop requirements, shading levels, water management, crop protection, and system configuration need to be considered in relation to these climatic variations.

- **Continental Climates (D):** Zone D is predominantly found in the higher latitudes of the Northern Hemisphere, including parts of Canada, Siberia, Scandinavia, and Alaska. Continental climates are characterized by pronounced seasonal temperature variation, with cold winters and relatively warm summers. Winter temperatures can fall substantially below freezing, while summer conditions may provide a defined but comparatively shorter growing season. Annual precipitation commonly ranges from approximately 300 to 600 mm in many continental regions, although substantial variation occurs across subtypes, with a significant proportion of precipitation falling as snow in colder areas. These conditions can influence crop selection, growing-season length, frost exposure, water availability, and agricultural operations. For AgriPV, system design may therefore need to account for seasonal crop requirements, snow loading, structural resilience, cold-weather operation, and opportunities for crop protection or season extension.

- **Polar and Highland Climates (E):** Zone E represents the coldest Köppen-Geiger climate group and includes tundra (ET) and ice-cap (EF) climates. Tundra conditions occur in areas such as parts of Alaska, northern Canada, Greenland, and other high-latitude regions, while ice-cap climates characterize Antarctica and the interior of Greenland. These environments have extremely low temperatures and limited conditions for conventional agricultural

production. Polar climates are therefore included here to provide completeness of the broader Köppen-Geiger classification but are excluded from the detailed AgriPV assessment undertaken in this framework. Highland or alpine environments are not treated as a separate Köppen-Geiger E subtype and should instead be considered according to their climatic conditions and elevation-specific characteristics.

The characteristics described above demonstrate that the climatic context can influence both agricultural requirements and the technical configuration of AgriPV systems. Temperature and seasonal variation affect crop selection, growing periods, and thermal conditions; precipitation and evaporative demand influence water availability and irrigation requirements; while solar radiation, humidity, wind, and extreme weather conditions can affect PV system configuration, structural design, crop microclimate, and operational practices. These relationships provide the basis for translating climate characteristics into AgriPV-specific priorities, as summarized in Table 1.

Table 1: Climatic zone characteristics and relevance for AgriPV

Climate Zone	Köppen-Geiger Classification	Key Climatic Characteristics	Agricultural Implications	AgriPV Design & Operational Implications
Tropical	A: Af, Am, Aw	High temperatures throughout the year; limited seasonal temperature variation; high humidity and substantial rainfall, with rainfall patterns varying across subtypes.	Long growing seasons and high crop diversity; crop productivity can be affected by heat, excessive rainfall, humidity and waterlogging.	Heat-stress reduction; crop-specific shading; drainage and moisture management; structural resilience under high rainfall and humidity.
Arid	B: BWh, BWk	Very low precipitation; high evaporative demand; water scarcity; substantial temperature variation, depending on location.	Strong dependence on irrigation; high crop-water stress; water availability is a major constraint on agricultural production.	Water conservation; reduction of soil evaporation; heat mitigation; efficient irrigation and crop-water management; consideration of dust/soiling.
Semi-arid	B: BSh, BSk	Low and seasonally variable precipitation; water-limited conditions; generally warm or hot conditions with varying seasonal temperature patterns.	Rainfall variability and water availability strongly influence crop selection and productivity.	Water-use efficiency; appropriate shading; crop-water management; heat-stress reduction; improved resilience to rainfall variability.
Temperate	C: relevant C subtypes	Moderate temperatures and distinct seasons; precipitation varies considerably across subtypes; occasional drought, flood and heat events.	Supports diverse agricultural systems and crops; productivity is influenced by seasonal temperature and rainfall patterns.	Crop-specific shading; seasonal microclimate management; water management; protection from climatic extremes.
Continental	D: relevant D subtypes	Pronounced seasonal temperature variation; cold winters and relatively warm summers; shorter growing seasons in many areas; snow and frost may occur.	Shorter growing periods; crop selection and agricultural operations influenced by frost, snow, temperature and seasonal water availability.	Season extension; frost and temperature protection; snow and wind loading considerations; structural resilience; seasonal system operation.
Polar*	E: ET, EF	Extremely low temperatures; tundra and ice-cap conditions; very limited conventional agricultural production.	Generally unsuitable for conventional open-field agricultural production.	Excluded from detailed AgriPV assessment because of limited relevance to conventional agricultural deployment.

The comparison above highlights that AgriPV requirements are strongly influenced by the climatic and agricultural context in which a system is deployed. The climatic characteristics summarized in Table 1 provide an important basis for understanding the opportunities and constraints associated with AgriPV across different regions. However, climate classification alone cannot capture the full range of factors that influence the feasibility, design, and performance of an individual AgriPV project. The application of the climate-zone approach is therefore subject to several limitations, particularly where site-specific agricultural, environmental, technical, regulatory, and economic conditions vary within the same climatic zone.

1.4 Limitations

While this Global AgriPV Framework has been developed to provide structured, practical, and climate-responsive guidance, it is important to recognize the scope and limitations within which these frameworks should be interpreted and applied. AgriPV is an evolving domain, and outcomes are inherently influenced by site-specific, institutional, and market conditions.

The key limitations of the frameworks are outlined below:

- **Context-specific applicability:** The recommendations provided in this framework are intended as a decision-support tool for policy makers and project developers. Actual system design, crop selection, and operational practices must be customized based on local site conditions, including soil characteristics, water availability, farm size, land tenure arrangements, and existing agricultural practices. The frameworks should therefore be adapted, rather than directly replicated, for individual projects.
- **Dependence on local data availability and quality:** Several aspects of AgriPV planning, such as crop performance under partial shading, microclimatic effects, yield impacts, and long-term O&M costs require reliable local data. In many regions, empirical field-level data on AgriPV remains limited. Where assumptions or proxy data are used, outcomes may vary once projects are implemented at scale.
- **Dynamic nature of technologies and practices:** Solar PV technologies, agricultural practices, and energy storage solutions are evolving rapidly. Advances in PV module efficiency, semi-transparent technologies, tracking systems, digital agriculture, and precision irrigation may alter design tradeoffs and economic outcomes over time. As such, the frameworks represent the current best practices and should be periodically updated to reflect technological and market developments.
- **Policy, regulatory, and institutional variability:** The framework does not account for the full diversity of national and sub-national policy, regulatory, and land-use planning regimes across ISA member countries. Project feasibility and bankability will be significantly influenced by local policies related to land classification, agricultural subsidies, power evacuation, tariffs, grid connectivity, and environmental approvals, which fall beyond the scope of this study.
- **Economic outcomes are subject to market conditions:** Financial performance of AgriPV projects is sensitive to crop prices, input costs, power tariffs, financing structures, and climate risks. While the framework highlights key economic considerations, it does not replace detailed projects specific financial modelling or investment due diligence.
- **Not a substitute for detailed engineering or agronomic design:** The frameworks are not intended to serve as a substitute for detailed engineering design, structural analysis, or agronomic planning. Project development should be supported by qualified engineers, agronomists, and other specialists to ensure compliance with local standards, safety requirements, and best practices.

Taken together, these limitations define the intended role of the framework as a structured decision-support resource rather than a prescriptive solution for individual projects. The climate-zone assessment provides a common basis for understanding how AgriPV considerations may vary across different contexts, while project-specific assessment remains necessary to

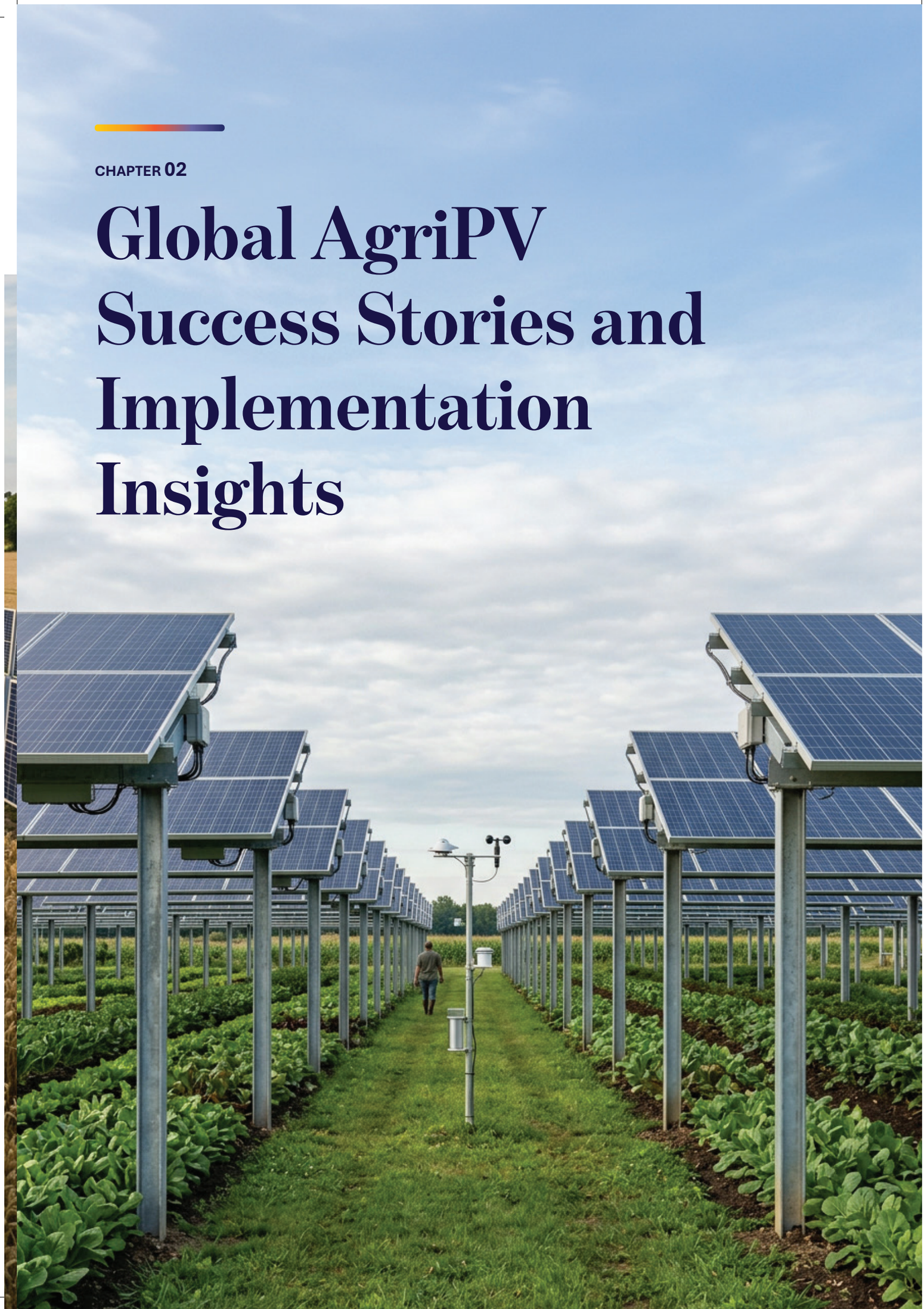
account for local agricultural, environmental, technical, regulatory, and economic conditions.

Building on this foundation, the next chapter moves from the broader climatic and agricultural context to the technical characteristics of AgriPV systems. It examines the principal system configurations, layout and structural considerations, crop–PV interactions, and other technical parameters that influence how AgriPV systems can be designed and adapted to different site conditions.



CHAPTER 02

Global AgriPV Success Stories and Implementation Insights



The growing interest in AgriPV is supported not only by research and pilot studies but also by a steadily expanding portfolio of successful commercial projects across the world. These legacy and operational case studies provide valuable evidence of how AgriPV systems perform under real farming, climatic, and market conditions. From vineyards in France and orchards in Italy to vegetable farms in Japan and large-scale agricultural systems in Germany, etc. Practical experiences have demonstrated that agricultural production and solar energy generation can coexist while creating value for farmers, developers, and communities.

The findings presented in this report are based on a comprehensive assessment of global AgriPV practices, supported by an extensive program of stakeholder engagement and case study analysis. The study combined a review of international policy frameworks, technology deployments, business models, and operational experiences with primary consultations conducted across the AgriPV value chain. A series of detailed case studies were evaluated to understand how AgriPV systems are being deployed across diverse agricultural and climatic contexts. These case studies covered a range of applications, including crop-based AgriPV, livestock-integrated systems, solar-powered irrigation, distributed agricultural energy systems, and utility-scale dual-use projects. Emphasis was placed on understanding the factors influencing project success, including regulatory frameworks, grid connectivity approaches, financing mechanisms, agricultural outcomes, and stakeholder acceptance. These engagements included policymakers, regulators, utilities, renewable energy developers, technology providers, farmer producers organizations (FPOs), agricultural experts, research institutions, financial institutions, industry associations, and development agencies.

Such consultations provided practical insights into the opportunities and challenges associated with AgriPV deployment, including land-use considerations, grid integration, crop compatibility, investment requirements, and implementation barriers.

To ensure that the assessment reflected the diversity of conditions across potential deployment regions, consultations and case studies were conducted across multiple climatic zones, including tropical, arid, semi-arid, temperate, and continental regions. This approach enabled the study to capture climate-specific considerations relating to crop productivity, water availability, solar resource quality, system design, and operational performance. The comparative assessment of experiences across these climatic zones also helped identify best practices and lessons that may be adapted to different market and agricultural contexts. The insights generated through stakeholder consultations were subsequently triangulated with global case studies, policy reviews, technical literature, and market data. This combination of primary and secondary research enabled the development of a robust evidence base framework **Global Agriphotovoltaics Climate-Zone Technical Framework a Symbiotic design considerations for agriphotovoltaic (AgriPV) systems in ISA member countries** across five climatic zones. By examining successful AgriPV implementations across different regions and agricultural systems, this chapter seeks to identify common success factors, emerging best practices, and transferable lessons. These insights provide a practical foundation for the climate-responsive design approaches, development toolkit, and implementation guidance presented in the following chapters, ensuring that future AgriPV projects can build upon proven experiences rather than starting from first principles.





2.1 Legacy AgriPV Project Case Studies

2.1.1 Case Study I - Jodhpur, Rajasthan, India

A. Brief of the project

The ICAR- Central Arid Zone Research Institute (CAZRI), an organisation situated in Jodhpur, Rajasthan, has set up a 105 KW AgriPV system (details in Table 2) with three experimental designs in three different blocks. The size of the farm where the experiment has been carried out is 68* 68, and the size of each experimental block is 28*28 m.[5]

Table 2: Key features of the specified project site:

Given Parameters	Details
System Capacity	105 kW
Commissioning year of the project	2017
Location of the project	Central Arid Zone Research Institute (CAZRI) in Jodhpur
Land Area of the project	68*68 m
Climatic Zone	Arid
Crops cultivated	Mung Bean, Moth Bean, Cluster Bean, Chickpea, Cumin, Isabgol, Aloevera, Sonamukhi, Sankhpushpi, Chilli, Cabbage, Onion, Garlic, Brinjal, Spinach, Snap melon
Some other parameters	**Details**
Average annual sunshine duration	11.91 hours per day
GHI	5.7 to 6.0 kWh/m^2/ day
Average annual rainfall	323 mm
Average annual temperature	26.5 degree Celsius[6]
Soil Type	Sandy and loamy soil[7]

5 https://www.researchgate.net/publication/352061905_Agrivoltaic_system_A_novel_technology_for_doubling_the_farmer's_income_in_hot_arid_ecosystem_of_western_Rajasthan_India
6 https://en.climate-data.org/asia/india/rajasthan/jodhpur-2848/
7 https://energyforum.in/fileadmin/india/media_elements/Photos_And_Gallery/20201210_SmarterE_AgroPV/20201212_NSEFI_on_Agriphotovoltaics_in_India__1_.pdf

a. Climate Zone Overview of the project

Jodhpur's BWh climate type indicates a hot desert climate with hot summers and mild winters, with almost no precipitation throughout the year. The average temperature is around 26.5 °C. Jodhpur receives very little rainfall, typically around 323 mm (12.7 inches) annually.

b. Crop overview/agricultural overview

Scenario of Crop Cultivation in Jodhpur

The soil profile of Jodhpur is predominantly sandy and loamy, characteristic of its arid climate. Bajra (pearl millet) is a major crop in the Kharif season, while wheat, pulses, and spices like cumin, coriander, and red chilies are grown during the Rabi season. The district is known for red chilies, onions, garlic, and is a major production centre for guar.

Crops cultivated in the AgriPV Project

Various types of Annual and Perennial crops across the Kharif and Rabi seasons are cultivated in the inter-row spaces between the panels in the current AgriPV Project. Various annual and perennial crops are cultivated within the AgriPV experimental blocks. Kharif crops include mung bean, moth bean, and cluster bean. Rabi crops include isabgol, cumin, and chickpea. Perennial crops include Aloe vera and Shankhpushpi. Selected vegetables have also been evaluated. Crop placement varies across the experimental arrays according to the available inter-row spacing and the objectives of each trial and is given in Table 3.

Table 3: Crops Cultivated between the installed arrays based on the available inter-row spacing

Type of Array	Type/Season of Crops	Name of the Crops
Array 1 (Inter-row spacing of 3.2 m)	Perennial Crops	Aloe vera, Shankhpushpi
Array 2 (Inter-row spacing of 6.4 m)	Rabi Crops	Isabgol, Cumin, Chickpea
Array 3 (Inter-row spacing of 9.6 m)	Kharif Crops	Mung Bean, Moth Bean and Cluster Bean



RATIONALE FOR CROP SELECTION

Shade Tolerance & Yield Response

- *Spinach is considered a relatively shade-tolerant crop, making it suitable for AgriPV projects where partial shading from solar panels is present. Leafy greens like spinach, along with lettuce and kale, are known for their ability to grow under a range of solar panel configurations.*
- *Onions, Cabbage, Chilli and eggplants show stable to slightly improved yields under partial shade due to microclimate moderation.*
- *Beans can be grown in AgriPV systems, but their shade tolerance varies depending on the bean variety and the level of shading provided by the solar panels. While some varieties may thrive in moderate shade, excessive shading can negatively impact yield and maturity.*
- *While not highly shade-tolerant, Isabgol can be grown in AgriPV systems, particularly in areas where the shading is not excessive or is seasonal.*
- *Aloe vera demonstrates good shade tolerance and can thrive in the shaded areas beneath or between solar panels. Studies have shown that the microclimate created by solar panels can even benefit Aloe vera growth, potentially mitigating stress caused by high solar radiation and temperature.*

Water and Irrigation requirements

- *In AgriPV, beans can have lower water requirements compared to conventional farming due to reduced evaporation and increased moisture retention. The shading effect of solar panels and increased humidity can lead to improved water use efficiency.*
- *Aloe vera is a drought-tolerant plant and generally requires infrequent watering, especially in arid regions. Isabgol is also relatively drought-tolerant and requires less water than many other crops.*
- *Cabbage, with a typical water requirement of 2.57 to 5.81 mm/day, can benefit from the reduced evaporation under the panels, potentially leading to water savings.*
- *Brinjal, on the other hand, generally requires loose, well-drained soil and is susceptible to waterlogging. The reduced sunlight under the panels might also affect Brinjal's growth and yield, requiring careful management of water and soil conditions.*

Height and Growth Habit

- *Mung Beans and Cluster Beans belonging to the Bush Type Beans family which typically reach a mature height of around 1 to 3 feet which forms a perfect fit for cultivation between and beneath the panels.*
- *Isabgol and Aloevera is often selected for its relatively short height and ability to withstand some shade, making it suitable for intercropping between solar panel rows.*
- *Cumin plants are generally low growing, reaching a height of about 30-45 cm (12-18 inches). Cumin plants, with their moderate height and branched structure, are well-suited for AgriPV systems as they can effectively utilize available sunlight and space beneath elevated solar panels.*
- *Cabbage grown under AgriPV generally reaches heights of around 20-30 cm during their peak vegetative stage, with some varieties reaching up to 31 cm. The growth habit is characterized by a dense, rounded head formation, with minimal differences in size compared to cabbages grown in open fields.*

c. Solar Photovoltaic potential overview

This project in Jodhpur features monocrystalline solar panels arranged in five experimental designs spread across three distinct blocks. Each block has an installed solar capacity of 35 kW. The variations in design are based on two key parameters: module density and the number of rows. As depicted in Figure 2, the row designs are categorized into three types: (a) One Row PV Array (ORPVA)-Array 1, (b) Two Row PV Array (TRPVA)-Array 2, and (c) Three Row PV Array (ThRPVA)- Array 3.

Accordingly, the five experimental designs installed are outlined as below:

- One Row PV Array with full density
- One Row PV Array with half density
- Two Row PV array with full density of lower row and half density of upper row
- Three Row PV array with full density of bottom and middle row and half density of top row
- Three Row PV array with full density of bottom row and half density of middle and top row.

The spacing between rows is 3.2 meters for ORPVA, 6.4 meters for a TRPVA, and 9.6 meters for a ThRPVA. The mounts are approximately 1.22 meters high for the single-row PV array, 1.94 meters for the double-row PV array, and 2.66 meters for the three-row PV array. These features have been represented in Figure 3, Figure 4, Figure 5.

Figure 2: Five types of experimental AgriPV designs

The five types of designs

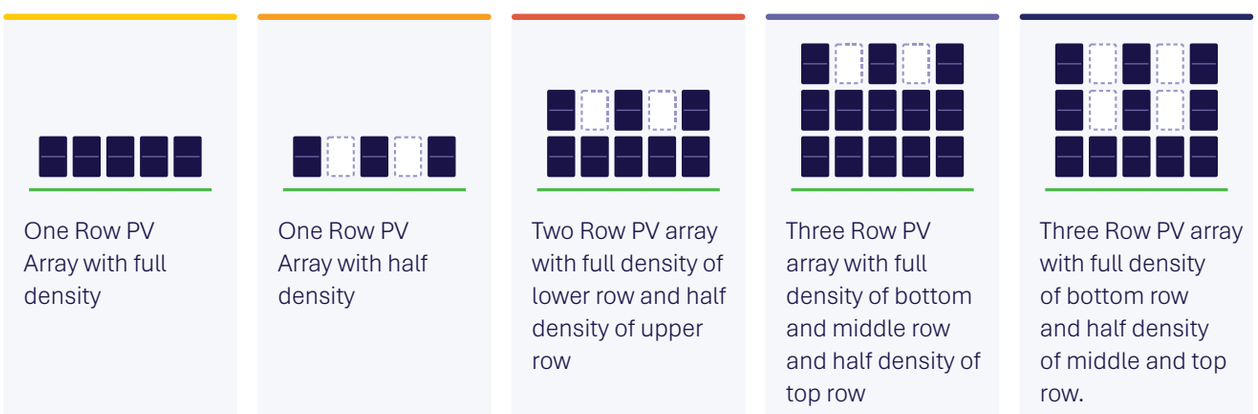


Figure 3: One Row PV Array (ORPVA)

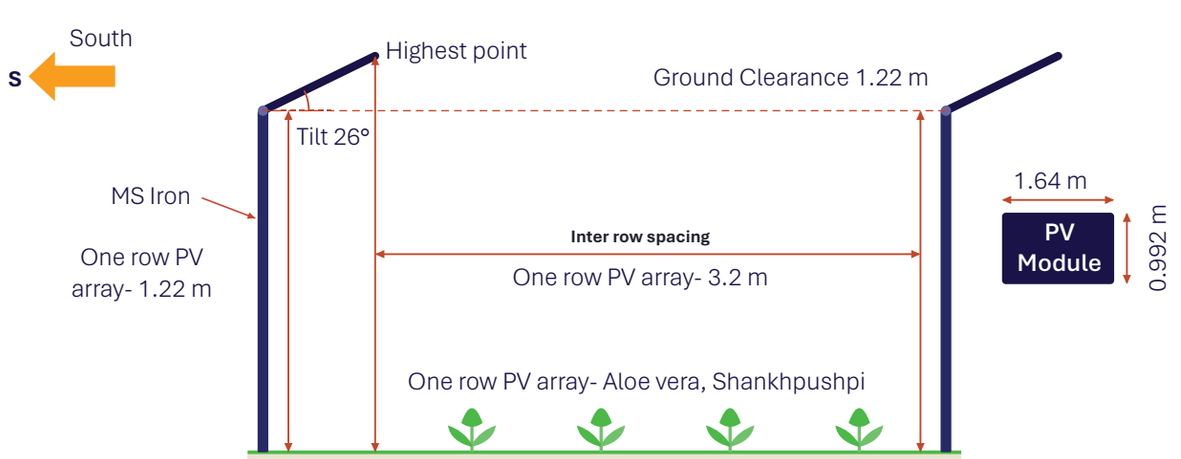


Figure 4: Two Row PV Array (TRPVA)

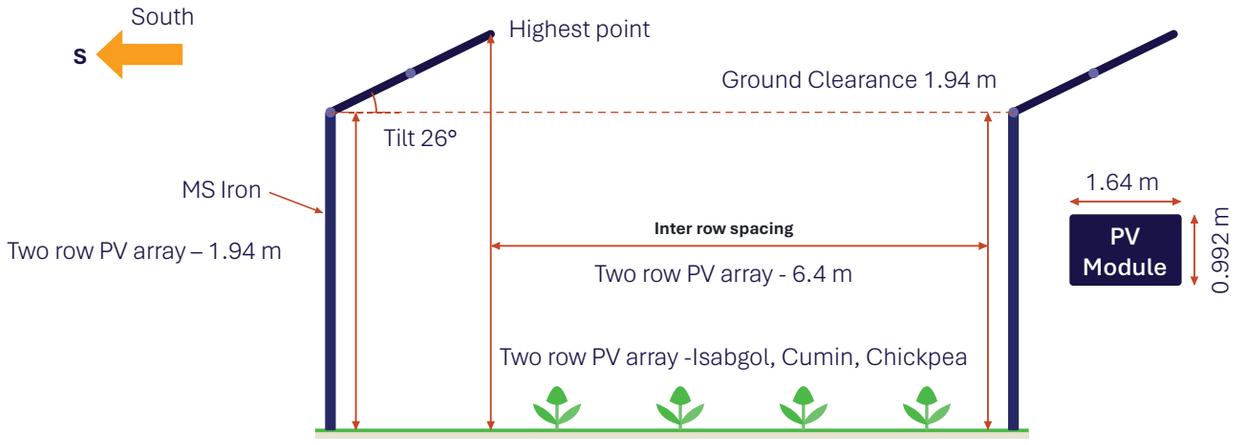


Figure 5: Three row PV Array (ThRPVA)

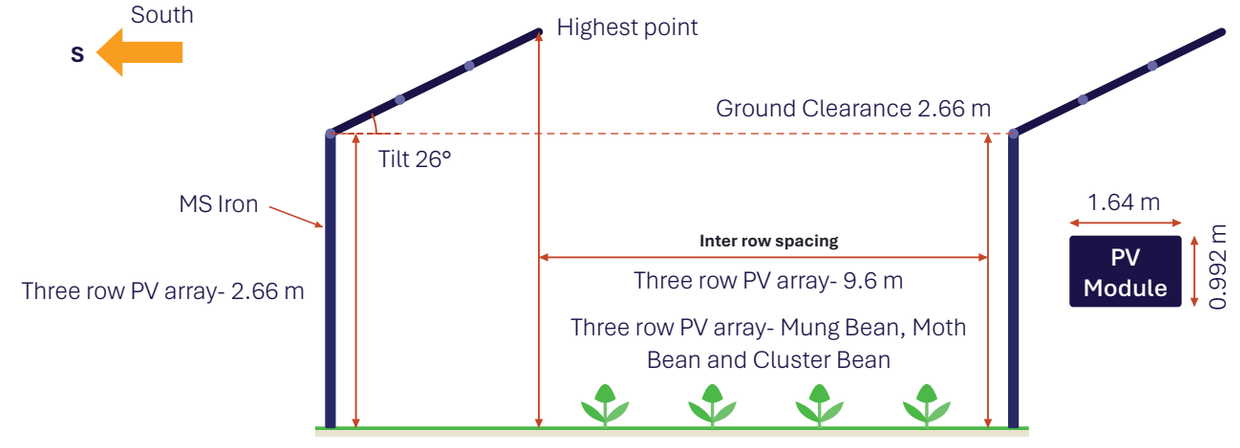
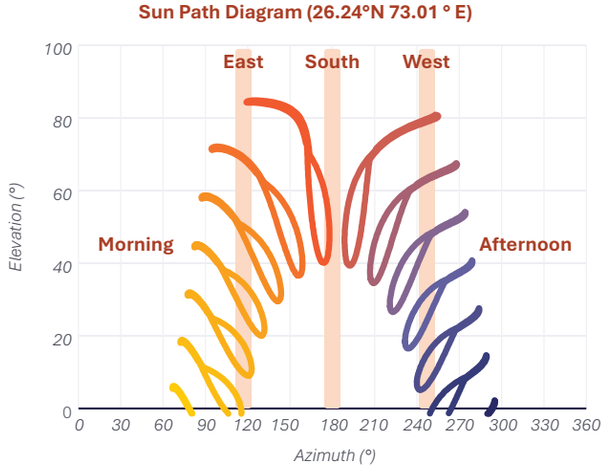


Figure 6: Sun Path Diagram for the specified project Site



For the project site, the sun path diagram has been plotted and presented in Figure 6. According to Global Solar Atlas, the optimum tilt for south facing fixed tilt PV array in Jodhpur around **30^0**. Orienting the panels at this angle can maximize the total solar irradiation received on a tilted surface throughout the year.

To calculate inter-row spacing, the sun elevation angle can be considered from the sun path diagram. In this case it is considered to be 35 degrees. Considering the height difference of 0.71 m between the lowest point and highest point of the PV array, the minimum inter row spacing between the two PV arrays should be **around 1.01 m**.[8]

8 The module length as depicted in figure is 1.64m and tilt angle is 26 degrees. So, the height between lowest and highest point of the module will be sin (26) *1.64m which will be equal to 0.71m. To get the elevation angle the window considered in the sun path diagram is 10 AM to 2 PM during winter solstice for worst case scenario. The solar elevation in this case would be 35 degrees. Hence, the shadow length would be height difference / tan (solar elevation) which in this case is 0.71/tan (35) = 1.01m

B. Comparative analysis of design aspects of AgriPV project with ground-mounted project

For estimating the power generation from the hypothetical project, the team has made use of the photovoltaic power potential provided over Global Solar Atlas at the project coordinates approximated as that of Jodhpur Rajasthan. The project design of the hypothetical ground-mounted solar PV system follows common industry frameworks for such setups.

Considering the previously mentioned parameters for the AgriPV system in Jodhpur, the comparative analysis between a hypothetical conventional ground-mounted system and an AgriPV system is shown in the Table 4

Table 4: Comparative Analysis between a hypothetical conventional ground-mounted system and an AgriPV system and observations thereof:

Parameter	For AgriPV (Array 1)	For conventional ground-mounted solar PV (estimated)	Remarks
COMMON DESIGN PARAMETERS			
PV panel	Monocrystalline Si PV	Monocrystalline Si PV	Some base parameters have been considered to be same for the AgriPV system as well as the ground-mounted system
PV panel dimensions (length and width)	1.62 m*0.992 m (260 W)	1.62 m *0.992 m (260 W)	
Solar tracking	None, fixed tilt	None, fixed tilt	
Material of PV panel columns, rafters, and purlins	MS Steel	Hot dip Galvanized Mild Steel	
Project Area	2352 m^2	2352 m^2	
DIFFERENT DESIGN PARAMETERS			
Azimuth direction	South facing	South facing	
Tilt angle (degrees)	26 degrees	30 degrees	Optimal tilt angle of a conventional ground-mounted system In Jodhpur is significantly greater than the tilt angle of AgriPV system.
Ground clearance (lowest height of PV panel from ground)	1.22 m	0.6 m	AgriPV systems differ significantly from ground-mounted systems in terms of ground clearance and inter-row spacing, primarily to accommodate agricultural activities beneath the solar panels.
Interrow spacing	3.2 m	1.01 m	
DC System Capacity	105 kWp	142 kWp[9]	Design difference allows more modules to be installed in ground-mounted PV project, which justifies the capacity difference when compared to the AgriPV project.
Approx number of PV panels	404	547	
Ground Coverage Ratio	28%	38%	Higher ground coverage ratio is due to higher number of modules in ground-mounted system.
COMPARISON OF GENERATION			
Annual Generation per kWp	1231.10 kWh	1748.3 kWh	The generation on unit capacity basis is lesser than ground-mounted PV project may be because of the difference in tilt angle between the AgriPV and the ground-mounted project.
Capacity Utilization Factor[10] (CUF on AC side)	14%	19%	

9 Considering inter-row distance of 1.2 m, and additional 50% space requirement, 1 kWp project would require project area of 16.6 m^2, hence 142 kWp of project can be installed on project area of 2352 m^2

10 CUF is metric used to evaluate the performance of a power project and is defined as the ratio of the actual output of a power project over a year to its potential maximum output if it operated at full capacity continuously over the same period.

Table 4: (continued) Comparative Analysis between a hypothetical conventional ground-mounted system and an AgriPV system and observations thereof:

Parameter	For AgriPV (Array 1)	For conventional ground-mounted solar PV (estimated)	Remarks
Annual Generation per m²	54.96 kWh	105.552 kWh	The generation on unit land basis is significantly lower for AgriPV project.
Annual Energy Production	129266 kWh/year	248258.6 kWh/year	The overall energy generation from the conventional PV system is nearly double that of the AgriPV system. This is primarily due to the higher installed capacity in the conventional setup and a significantly higher tilt angle in case of ground-mounted.

Hence, if the land had been exclusively used for power generation, it is estimated that there would be double the power generation as compared to the AgriPV system.

C. Impact on PAR and Crop Yield in the AgriPV Project

It is observed that the plant selection for cultivation under AgriPV systems is dependent on certain factors including height of the plant (preferably less than 50 cm for cultivation in arid regions), certain amount of shade tolerance and less water requirement and is presented in Table 5.

Table 5: Impact on yield of various crops cultivated in the AgriPV systems

Crop Category	Crops	Reduction in Photosynthetically Active Radiation (PAR) in comparison to Open Field Scenario	Impact on Yield in comparison to Open Field Scenario
Kharif Crops	Mung Bean	7%	4.6% ↓
	Moth Bean	–	8.6% ↓
	Cluster Bean	–	11.8% ↓
Rabi Crops	Chickpea	47%-59%	6.6% ↓
	Cumin	42%-44%	10.3% ↓
	Isabgol	32%-54%	7.8% ↓
Perennial Crops (Medicinal Plants)	Aloevera, Sonamukhi, Sankhpushpi	–	Yield and Growth of Aloevera was significantly lower due to shading effect
Vegetables	Chilli, Cabbage, Onion, Garlic, Brinjal, Spinach, Snap melon	–	Yield and Growth of Brinjal was significantly lower due to shading effect No significant yield difference in case of spinach and snap melon



D. Inferences

- **Energy generation-** In Jodhpur, the conventional PV system can generate nearly twice as much energy as the AgriPV system. This difference is due to the higher tilt angle and higher ground coverage in the conventional ground-mounted system. Additionally, the conventional system benefits from a higher installed capacity on the same land area.

  Panel soiling is another key factor contributing to the reduced energy yield in the AgriPV system, with measured levels ranging between 3 to 4.5 g/m^2. According to a research study, soiling levels of 6 g/m^2 in arid regions can cause up to a 21.5% drop in energy output[11]. This suggests that current soiling levels in this AgriPV system are significantly impacting performance, making it a major contributor to the lower generation observed.

- **Project capacity-** The AgriPV project features wider inter-row spacing—3.2 meters for ORPVA, 6.4 meters for TRPVA, and 9.6 meters for ThRPVA—compared to just 1.2 meters in a conventional ground-mounted solar PV system. This increased spacing limits the number of modules that can be installed within the same land area. Consequently, the total capacity that could potentially be installed in the project area is 35.2% higher than the capacity of the AgriPV system.

- **Project operational parameter:** The Capacity Utilization Factor (CUF) on the AC side for the AgriPV project is around 14% while a hypothetical ground-mounted solar PV project has CUF of 19%.

- **Rainwater harvesting for dual water use-** The AgriPV system integrates a rainwater harvesting setup using PV module surfaces, underground PVC piping, and a 100,000-liter storage tank. It harvests up to 150,000 Liters of rainwater annually with an efficiency of 70–80%. This system not only reduces the need for external water for PV cleaning (20–40 L/kW/month) but also supports irrigation, providing up to 40 mm of water per acre during the rabi season.

- **Land Equivalent Ratio -** It displays a land equivalent ratio of 1.41, emphasizing the efficiency and synergy achieved in dual use of land.

- **Environmental Impact:** The Project facilitates reduction in soil erosion by wind, soil moisture conservation by reducing wind speed on ground surface, reduction in GHG emissions (598 tons of CO2 savings/ha/year).

This case study investigates a 105-kW AgriPV system at the Central Arid Zone Research Institute (CAZRI) in Jodhpur, India, a region with a hot desert climate. The project explored five different panel configurations across three blocks, varying module density and row numbers. A key finding is the significant difference in energy production between the AgriPV system and a comparable conventional system. The east/west orientation of the AgriPV panels, necessary for accommodating inter-row crop cultivation, resulted in roughly half the energy output of a south-facing conventional system. This underscores the trade-off between maximizing energy generation and enabling agricultural activities within the same land area. Furthermore, wider spacing in the AgriPV system (3.2m-9.6m vs. 1.01m in a conventional system) further limits the installable capacity. Despite these limitations, the project achieved a 1.41 land equivalent ratio, demonstrating the synergistic benefits of dual land use. The integrated rainwater harvesting system, providing both PV panel cleaning and supplemental irrigation, further enhances the system's value, particularly in this arid environment. While certain crops like brinjal and aloe vera experienced reduced yields due to shading, others showed minimal impact or even benefited from the modified microclimate. This highlights the importance of careful crop selection for AgriPV systems in arid climates. The system's overall success in this challenging environment showcases the potential of Agriphotovoltaics for sustainable land management, combining renewable energy generation with enhanced water resource management and diversified agricultural production.

11 https://www.sciencedirect.com/science/article/pii/S2352484724003792



LEGACY AGRIPV PROJECT CASE STUDIES

2.1.2 Case study II - Junagadh, Gujarat, India

A. Brief of project

The Department of Renewable Energy Engineering at the Junagadh Agricultural University (JAU), designed and installed an experimental AgriPV System (details in Table 6) over an agriculture land. This AgriPV system was considered for evaluating performance of the solar PV system for a period of a year, focusing on power generation, average system efficiency, capacity factor, and overall performance ratio. The aim of this study was to assess the AgriPV system performance in accordance with the International Energy Agency (IEA).[12] The key features of the project site are given in the following table.

Table 6: Key Features of the Specified Project Site

Given Parameters	Details
System Capacity	7.2 kW
Commissioning year of the project	2022
Location of the project	College of Agricultural Engineering and Technology (CAET) Junagadh
Land Area of the project	153.88 m^2
Crops cultivated	Tomato, Capsicum and Cucumber
Climatic Zone	Semi – arid
OTHER PARAMETERS	**DETAILS**
Average annual sunshine duration	3243.44 hours
Average annual rainfall	657 mm
Average annual temperature	25.7 degrees Celsius[13]
Soil Type	Medium black soil[14]
Soil Texture	Calcareous, with patches of alluvial and coastal saline soils

12 https://www.researchgate.net/publication/372454580_Case_Study_on_Power_Generation_from_Agrivoltaic_System_in_India
13 https://en.climate-data.org/asia/india/gujarat/junagadh-5044/
14 https://energyforum.in/fileadmin/india/media_elements/Photos_And_Gallery/20201210_SmarterE_AgroPV/20201212_NSEFI_on_Agriphotovoltaics_in_India__1_.pdf

a. Climatic Zone Overview of Project

Junagadh, located in the Saurashtra region of Gujarat, India, falls within the **hot semi-arid (BSh)** Köppen climate zone, as part of the broader Gujarat Plains and Hills Agro-Climatic Zone. Junagadh receives an average annual rainfall of 657 mm, primarily during the southwest monsoon (June–September). Mean annual temperature is around 25.7°C. Summers (April–June) are hot, with maximum temperatures reaching 38–42°C, while winters (November–February) are mild, with minimums of 10–15°C. May is typically the hottest month, and January the coolest, per climate data from Patel et al. (2015).

b. Crop Overview/ Agricultural Overview

Scenario of Crop Production in Junagadh, Gujarat

Junagadh's agricultural scenario is dominated by rainfed farming, with 6.90 lakh ha under cultivation out of a 10.48 lakh ha geographical area, per JAU[15]. The major crops grown are **groundnut, cotton, pearl millet (bajra), sesame, wheat, and coriander**, selected for their tolerance to semi-arid conditions and market demand. Horticultural crops like **mango, onion, and vegetables (tomato, brinjal etc.,)** are also significant but occupy smaller areas due to irrigation constraints.

Crops cultivated in the AgriPV Project

Based on global AgriPV research and pilot projects, shade-loving or shade-tolerant vegetables are typically the most suitable crops for cultivation in these systems. Leafy greens, and other cool-season vegetables often show enhanced growth, yield, and quality under AgriPV systems. The current AgriPV project facilitated the cultivation of Tomato, Capsicum and Cucumber beneath the overhead elevated solar panels.

15 Junagadh Agricultural University-Articles



RATIONALE FOR CROP SELECTION

Shade Tolerance & Yield Response

- ***Tomato:*** *Tomato plants generally exhibit high shade tolerance, making them a suitable crop for AgriPV systems, where photovoltaic (PV) panels create shading. Studies have shown that tomatoes grown under shaded conditions (like those in AgriPV) can have larger fruits with reduced sun burn compared to those in full sunlight. However, the amount of Relative Shading Ratio (RSR) plays a key role in determining the suitability.*[16]
- ***Cucumber:*** *Cucumber is moderately tolerant to shade conditions exhibiting varying levels of yield under different shade conditions. In hot climates, maximum crop yields are typically achieved with shading levels up to 35%. Yield gains for cucumber under AgriPV are only expected in hot climates.*
- ***Capsicum:*** *Capsicum, commonly known as peppers, is generally considered a shade-tolerant crop that can be successfully grown under AgriPV. Many pepper varieties can tolerate shade, particularly a reduction of 35% to 50% in photosynthetically active radiation (PAR).*

Water Stress and Irrigation requirements:

Tomatoes generally need 400-600 mm of water over their 90–120-day growth cycle. Pepper water requirements can range from 600 to 900 mm for the entire growing period, and up to 1250 mm for long growing periods and multiple pickings. However, these plants exhibit moderate tolerance to water stress and can thrive in AgriPV (AgriPV) systems due to reduced sunlight periods, lower evaporation rates, and consequently, decreased irrigation requirements.

Height and Growth Habit:

The elevated and stilt mounted structure of solar panels provide a readily available structure for supporting crops such as Tomato, Cucumber etc., Further these crops can be grown in AgriPV systems with significantly lower ground clearance.

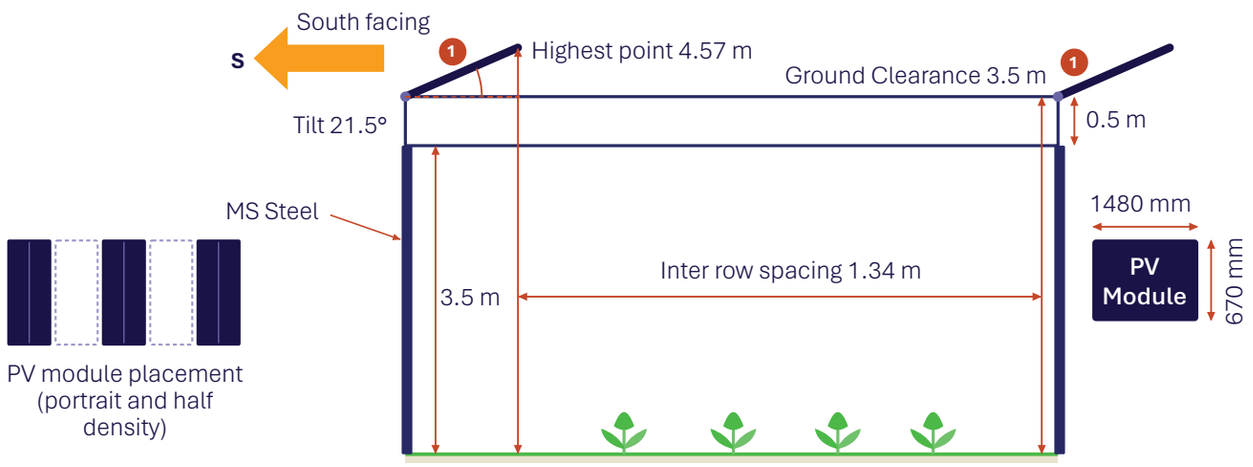
c. Solar Photovoltaic Potential Overview

The AgriPV system described in the research article, has 48 polycrystalline solar panels (each panel- 150W) which are installed and arranged in 4 rows in south facing direction, with 12 panels in each row. The rows are spaced 1.34 m apart, and the mounts are about 3.5 m high shown in Figure 7. The panels in this AgriPV system are tilted at an angle of 21.5 degrees.



16 It should be noted that the reported tomato and capsicum outcomes demonstrate performance under the specific Junagadh system and should not be generalized as intrinsic crop responses to AgriPV shade. Interpretation should identify the cultivar, crop season, crop-zone light conditions, irrigation and nutrient management, marketable-yield definition, comparison plot, replication, and observation period. These results indicate local potential but do not establish a universal percentage benefit for tomato or capsicum under other AgriPV configurations.

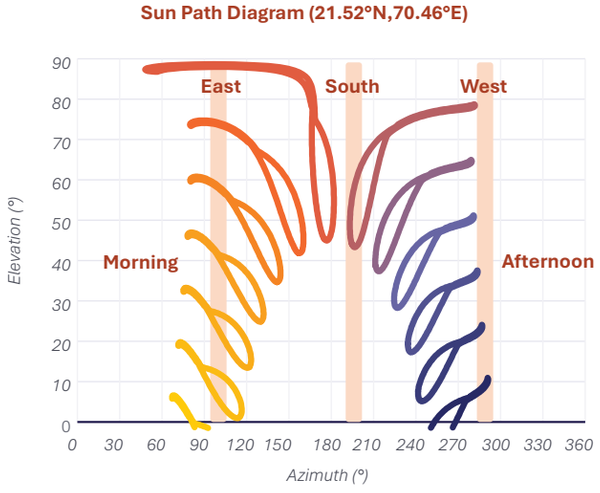
Figure 7: Specified PV structure design and system's architectural implementation within this AgriPV project.



For the project site, the sun path diagram has been plotted and presented in Figure 8. The optimum tilt angle is based on maximizing the total solar irradiation received on a tilted surface throughout the year. According to Global Solar Atlas, the optimum tilt for south facing fixed tilt PV array in Junagadh around **26^0**.

Considering a height difference of 0.57 m between the lowest point and highest point of the PV array depicted in the diagram above, and in conjunction with the sun path diagram, the minimum inter row spacing between the two PV arrays should be **around 0.8 m**.

Figure 8: Sun Path Diagram for the specified project Site



B. Comparative analysis of design aspects of AgriPV project with ground-mounted project

The performance of the AgriPV system can be evaluated based on its yield and the capacity utilization factor (CUF) of the project. This evaluation allows us to compare the AgriPV system with a traditional ground-mounted system, helping us understand the differences between an AgriPV system and a standard PV system.

For estimating the power generation from the hypothetical conventional ground-mounted project, the team has made use of the photovoltaic power potential provided over Global Solar Atlas at the project coordinates approximated as that of Junagadh Gujarat. The project design of the hypothetical ground-mounted solar PV system follows common industry frameworks for such setups and has been mentioned in the below table.

Considering the previously mentioned parameters for the AgriPV system, Table 7 shows the comparative analysis between AgriPV system and ground-mounted system is as follows:

Table 7: System design comparison for Junagadh, Gujarat case study

Parameter	For AgriPV Project (Case Study)	For conventional ground-mounted solar PV (estimated)	Remarks
COMMON DESIGN PARAMETERS			
PV panel	Poly C-Si, 150 Wp	Poly C-Si, 150 Wp	Some base parameters have been considered to be same for the AgriPV system as well as the ground-mounted system
PV panel dimensions (length and width)	1480 *670 mm	1480 *670 mm	
Solar tracking	None, fixed tilt	None, fixed tilt	
Material of PV panel columns, rafters, and purlins	MS Steel	Hot dip Galvanized Mild Steel	
Project Area	153.88 m^2	153.88 m^2	
DIFFERENT DESIGN PARAMETERS			
Azimuth direction	South Facing	South facing	
Tilt angle(degrees)	21.5	26	Optimal tilt angle of a conventional ground-mounted system In Junagadh is significantly greater than the tilt angle of AgriPV system.
Ground clearance (lowest height of PV panel from ground)	3.5 meters	0.6 m	AgriPV systems differ significantly from ground-mounted systems in terms of ground clearance and inter-row spacing, primarily to accommodate agricultural activities beneath the solar panels.
Interrow spacing	1.34 meters	0.8 m	
DC System Capacity	7.2 kWp	9.38 kWp[17]	Design difference allows more modules to be installed in ground-mounted PV project, which justifies the capacity difference if compared to AgriPV.
Approx number of PV panels	48	63	
Ground Coverage Ratio	29%	40.5%	Higher ground coverage ratio is primarily due to higher number of modules on the same land area.
COMPARISON OF PROJECT GENERATION			
Annual Generation per kWp	1403 kWh	1673 kWh21	The generation on unit capacity basis is lesser than ground-mounted PV project which can be because of the tilt angle difference between the AgriPV system and the ground-mounted system.
Capacity Utilization Factor[18] (CUF on AC side)	16%	19%	
Annual Generation per m^2	65.66 kWh	101.97 kWh	The generation on unit land basis is significantly lower for AgriPV project.
Annual Energy Production	10105 kWh/year	15692 kWh/year	Overall generation is lower for AgriPV project due to lower installed capacity.

17 Considering inter-row distance of 0.8 m, and additional 50% space requirement, 1 kWp project would require project area of 16.4 m^2, hence 9.38 kWp of project can be installed on project area of 153.88 m^2

18 CUF is metric used to evaluate the performance of a power project and is defined as the ratio of the actual output of a power project over a year to its potential maximum output if it operated at full capacity continuously over the same period.

Hence, if the land had been exclusively used for power generation, it is estimated that there would be about 55% higher power generation.

C. Impact on Crops during the AgriPV Project[19]

The soil type prevalent in this region is black soil, which is highly suitable for vegetable cultivation. The major crops cultivated are Tomato, Cucumber and Capsicum under open cultivation system along with solar panels. During the three-month growing season, the light levels, air temperature, and relative humidity using sensors mounted above the soil surface, soil temperature and moisture were monitored to evaluate the impact of shading on the yield of the crops. The following results were reported in terms of crop yield, water-use efficiency and soil-moisture retention.

- **Crop Production:** Total Tomato/Capsicum fruit production was three times greater in AgriPV system in comparison to the open field conditions.
- **Water-Use Efficiency:** Water-use efficiency for the cucumber is 152% greater in the AgriPV system. For the cherry tomato, water-use efficiency was 60% greater and total fruit production got doubled in comparison to the open-field systems.
- **Soil-Moisture Retention:** Soil moisture retention was approximately 5% higher with daily irrigation and 14% higher with weekly irrigation.

D. Inferences

The following are the key inferences drawn from the case study by the project team:

- **Project design:** The research article and accompanying project image suggest that the PV panel columns in the AgriPV project are significantly thicker in diameter compared to those used in conventional ground-mounted projects. This increased thickness provides the necessary structural support for the elevated structure, which has a ground clearance of 3.5 meters, highest point of panel at around 4.57 m and a tilt angle of 21.5°. Due to the higher elevation, the AgriPV structure faces considerably greater wind-induced structural loads than ground-mounted solar PV systems.
- **Energy generation:** The energy production difference of approximately 5000 kWh/year on the same piece of land can be attributed to:
  - The higher ground coverage of a conventional PV system and the tilt angle. While the optimal tilt angle for Junagadh is 26 degrees, the AgriPV project maintains a tilt angle of 21.5 degrees.
  - Additionally, the inter-row spacing for a conventional system is around 0.8 meters, whereas for the AgriPV project, it is about 1.34 meters. This increased spacing allows for less panels to be installed in the AgriPV system.
- **Project operational parameter:** The Capacity Utilization Factor (CUF) for the AgriPV project is around 16% while a hypothetical ground-mounted solar PV project has CUF of 19%. While more study is needed to find the exact reason, one likely cause of the lower performance in the AgriPV system could be the tilt angle of the solar panels. They are set at 21.5 degrees, but the ideal angle for Junagadh as discussed earlier, is 26 degrees, which could affect how much sunlight the solar panels capture.
- **Improved Water-Use Efficiency and Soil Moisture:** Increased water-use efficiency of cucumber and tomato can be attributed to reduced evapotranspiration, lower soil and air temperatures, improved soil moisture retention due to better micro-climatic conditions caused through existence of solar panels. Some studies have even suggested that cultivation of crops under solar panels can improve soil moisture retention by 15% when irrigation was performed every 2 days[20].



19 https://www.researchgate.net/publication/343415156_Advantage_of_Agriphotovoltaics_Across_the_Food-Energy-Water_Connection
20 https://doi.org/10.3390/su16188271

This 2022 study from Junagadh Agricultural University (JAU) in Gujarat, India, evaluated a 7.2 kW AgriPV system's performance in a hot semi-arid climate. The system, featuring south-facing panels tilted at 21.5 degrees, was used to cultivate tomatoes, capsicum, and cucumbers. A key finding was the significantly improved crop production under the AgriPV system. Tomato and capsicum yields tripled compared to open field conditions, while cucumber water-use efficiency increased by 152%. These improvements are likely attributable to the partial shading provided by the panels, which mitigated heat stress and improved soil moisture retention (5% higher with daily irrigation and 14% higher with weekly irrigation) in this arid climate. However, the AgriPV system's energy generation was lower than a comparable conventional system due to the wider inter-row spacing (1.34m vs. 0.8m) required for crop cultivation and a slightly suboptimal tilt angle (21.5 degrees vs. the recommended 26 degrees). This resulted in a lower overall capacity and annual energy production. The thicker support columns needed for the elevated structure also highlight the increased structural demands of AgriPV systems. Despite the lower energy output, the study demonstrates the substantial benefits of AgriPV for improving crop yields and water use efficiency in water-stressed regions. Optimizing panel tilt angle and exploring alternative panel configurations could further enhance both energy and agricultural output in future AgriPV projects in similar climates. The study underscores the potential of Agriphotovoltaics to address both food and energy security challenges in arid and semi-arid regions.





2.1.3 Case study III - Jiangsu, China

A. Brief of project:

This case study details the AgriPV project established by Shenzhen Energy Nanjing in Jiangsu Province, China. The project, commissioned in 2016, spans 46.67 hectares and has a capacity of 20 MW. Its multifaceted objectives encompass power generation, agricultural cultivation, sightseeing tourism, science exhibition, and AgriPV research and development. The facility generates approximately 24 million kWh of electricity annually.

Table 8, summarise the case study has been prepared based on the details from the published research article[21] and other secondary research sources. Later, the researchers experimented with the panel height[22] in part of the AgriPV project to study the impact of shade on photosynthetic productivity and yield of fig production with different panel heights.

Table 8: Key technical and environmental parameters of the project, Jiangsu China

Given parameters	Details
System Capacity	20 MW
Commissioning year of the project	2016
Location of the project	Lishui, Jiangsu Province (31.62°N, 119.18°E)
Land Area of the project	4,66,700 m^2
Crops Cultivated	Fig
Climatic Zone	Temperate Continental Hot Summer
SOME OTHER PARAMETERS	**DETAILS**
Average annual sunshine duration	2145.8 hours
Average annual rainfall	1036.9 mm
Average annual temperature	15.5° C
Soil Type	Yellow loam soil (fertility and good drainage)

21 https://doi.org/10.3390/agronomy13071820 , last accessed on 7th May 2025
22 https://www.sciencedirect.com/science/article/abs/pii/S095965262500441X#:~:text=Figs%20are%20shade%2Dtolerant%20and,for%20enhancing%20efficient%20AVS%20production. Last accessed on 2nd June 2025

a. Climatic zone overview:

The project site is situated within a temperate Continental Hot Summer, as classified under the Köppen-Geiger climatic zone classification system. The site experiences an average annual rainfall of 1,036.9 mm, an average annual temperature of 15.5°C, and an average annual sunshine duration of 2,145.8 hours. These climatic conditions significantly influence both photovoltaic performance and agricultural viability.

b. Crop/Agricultural Overview:

Scenario of Crop Production in the Jiangsu Region

Jiangsu province boasts a vibrant and diverse agricultural sector, significantly contributing to China's overall food security. Its advantageous geographical location, fertile plains, and subtropical climate make it ideal for cultivating a wide range of crops. Rice, Wheat and Maize are the dominant crops in the province, accounting for a larger share of crop production. Rice is primarily cultivated in the northern regions owing to the hot, humid summers and mild winters, whereas wheat is grown in southern regions experiencing hotter summers and milder winters. Jiangsu is also one of the major producers of rapeseed (mustard), which is the major source of canola oil in China. Various fruits (especially apples, peaches, pears, and grapes) and vegetables (tomatoes, leafy greens and cucumbers) are also cultivated owing to the favorable climatic conditions and soil types.

Crop cultivated in the AgriPV Project

Figs are one of the minor fruit crops cultivated in China, especially in the regions of Jiaodong peninsula, Sichuan, Weiyuan County, Xinjiang, particularly Kashgar. Figs are shade-tolerant and easy to plant, making them a common crop in AgriPV systems. Previous studies have shown that light-demanding fruit trees such as apple, pear, and grapes are commonly cultivated in AgriPV systems, achieving good economic benefits. However, figs are more shade-tolerant than these fruit trees, making them better suited to the complex environments within AgriPV systems caused by shading from PV panels. The current AgriPV entails cultivation of fig trees in the inter-row spaces of the solar panels.

RATIONALE FOR CROP SELECTION

Shade Tolerance & Yield Response:

Fig Trees prefer full sunlight conditions, while some varieties might be able to tolerate a little amount of shade with little impact on the yield (fruit production). When planning an AgriPV system with fig trees, it's crucial to consider the shade patterns created by the solar panels and choose fig varieties that might be able to tolerate the reduced and diffused light conditions.

Water Stress and Irrigation Requirements:

The water requirements of fig trees vary depending on their growth stage, environmental conditions, and soil type. While the vegetative, bud growth and flowering stage requires ample water, they can thrive limited water supply in the fruiting and the dormant stage. Fig trees have natural ability to withstand drought conditions due to their deeper root systems. Further, proper soil water drainage system should be ensured to prevent waterlogging in case of reduced evapotranspiration which can attract disease and pest infestations.

Height and Growth Habit:

Fig trees, typically maintained at heights between 10-15 feet (3-4.5 meters), can be compatible with certain types of mounted solar panels, especially elevated or adjustable ones. However, the broad spreading type canopy of fig trees might pose a challenge interrupting with the solar panels when not trained on a timely basis.

Feasibility of Intercultural Operations:

Fig trees require regular pruning to manage their height and maintain air circulation. This can be accomplished within AgriPVs if panels are sufficiently elevated or spaced apart. Further, implementing drip irrigation systems under the solar panels is effective for fig trees, providing the necessary moisture without interfering with panel infrastructure.

Climate Resilience:

Fig Trees are highly resistant to drought conditions as they possess deeper root systems that allow them to access water from deeper layers.

c. Solar PV Project Design Overview:

The solar PV project is engineered as a south-facing, horizontal-oriented, fixed-tilt system (Figure 9). The PV array incorporates four modules laid in landscape orientation across the width of the array. The module mounting columns are concrete poles, each with a diameter of 300 mm and extending approximately 2.9 meters above ground level. Based on the imagery provided in the research article, our analysis indicates that the purlins and rafters of the PV module array are constructed from mild steel. A preliminary graphical representation of the PV structure design has been developed to illustrate the team's understanding of the system's architectural implementation within this AgriPV project.

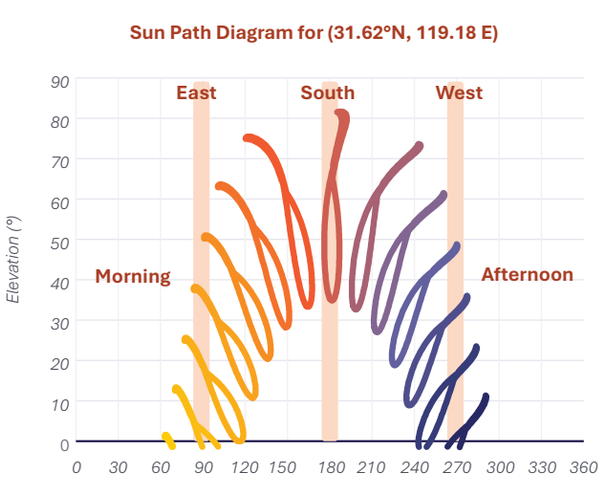
Figure 9: Specified PV structure design and system's architectural implementation within this AgriPV project.



For the project site, the sun path diagram has been plotted (Figure 10) to determine optimal solar energy capture. The optimal tilt angle for a south-facing fixed-tilt PV array, derived from maximizing annual total solar irradiation according to Global Solar Atlas[23] is 25^0.

Considering a height differential of 1.6 meters between the lowest and highest points of the AgriPV project PV array, and in conjunction with the sun path diagram, the minimum requisite inter-row spacing between adjacent PV arrays is determined to be 2.6 meters. The AgriPV project, however, implements a greater inter-row spacing of 3.2 meters to facilitate the inter-plantation of fig trees.

Figure 10: Sun Path Diagram for the specified project Site



23 https://globalsolaratlas.info/map?s=31.620161,119.180103&m=site&c=31.620161,119.180103,11 last accessed on 30th May 2025

B. Comparative analysis between AgriPV project and hypothetical ground-mounted solar PV project

A comparative analysis (Table 9) was conducted between the power generation of the AgriPV project and a hypothetical fixed-tilt ground-mounted solar PV project. The hypothetical project is assumed to be situated at the identical location and occupy the same land area of 466,700 m^2. Power generation estimates for the hypothetical project were derived using the photovoltaic power potential data provided by Global Solar Atlas[24] at the project coordinates. The design of the hypothetical ground-mounted solar PV system adheres to standard industry frameworks for such installations. The detailed comparative analysis is presented in the table below:

Table 9: System comparison for the Jiangsu, China, case study

Parameter	For AgriPV Project (Case Study)	For conventional ground-mounted solar PV (estimated)	Remarks
COMMON DESIGN PARAMETERS			
PV panel	Poly C-Si, 265 Wp rated	Poly C-Si, 265 Wp rated	Some base parameters have been considered to be same for the AgriPV system as well as the ground-mounted system
PV panel dimensions	1640 x 992 x 35 mm	1640 x 992 x 35 mm	
Solar tracking	None, fixed tilt	None, fixed tilt	
Tilt angle	24°	24°	
Azimuth direction	South facing	South facing	
Material of PV panel rafters and purlins	Mild steel	Hot dip Galvanized Mild Steel	
Project Area	4,66,700 m^2	4,66,700 m^2	
DIFFERENT DESIGN PARAMETERS			
Ground clearance (lowest height of PV panel from ground)	3.2 meters	0.6 m	Panel height and inter row spacing are increased to maximize light penetration to the ground, thereby facilitating agricultural activities.
Interrow spacing	3.2 meters	2.6 m	
Material of PV panel columns	Concrete	Hot dip Galvanized Mild Steel[25]	Concrete piles are used due to the elevated structure and higher loads in the AgriPV project, unlike conventional ground-mounted systems.

24 https://globalsolaratlas.info/map?s=31.620161,119.180103&m=site&c=31.620161,119.180103,11

25 Hot dip galvanized mild steel is used as columns in solar PV projects because it offers strong structural support, excellent corrosion resistance, and long-term durability in harsh outdoor conditions.

Table 9: (continued) System comparision for Jiangsu China case study

Parameter	For AgriPV Project (Case Study)	For conventional ground-mounted solar PV (estimated)	Remarks
DC System Capacity	23 MWp[26]	30.5 MWp[27]	Design differences allow for the installation of more modules in a ground-mounted PV project, resulting in a capacity differential.
Approx number of PV panels	86,792	115,094	
AC Capacity of the project	20 MW	26.5 MW	
Ground Coverage Ratio	27.6%	36.7%	Higher ground coverage ratio for conventional PV due to a greater number of modules.
COMPARISON OF PROJECT GENERATION			
Annual Generation per kWp	1,043.5 kWh	1,167.2 kWh[28]	The generation per unit capacity is comparable, though slightly lower for the AgriPV project.
Annual Generation per kW	1,200 kWh	1,343.4 kWh	
Capacity Utilization Factor[29] (CUF on AC side)	13.7%	15.3%	
Annual Generation per m^2	51.4 kWh	76.3 kWh	The generation per unit land area is significantly lower for the AgriPV project.
Land Equivalent Ratio (LER)[30] for Solar PV Project	0.67	1	
Annual Energy Production	24 million kWh/ year	35.6 million kWh/year	Overall generation is lower for the AgriPV project due to a lower installed capacity.

It is estimated that if the land had been exclusively utilized for power generation, the power output would be approximately 48% higher.

C. Impact on Crop Yield in the AgriPV Project

In the current AgriPV project, fig trees are planted in the inter-row spaces between the panels with an inter-tree spacing of 3m. The main growing season of figs in this site is April to October. The height of plants is about 1m with a root length of about 0.3m (Table 10). The impact of shade on photosynthetic productivity and yield of a crop component is studied as a part of crop research with an aim to determine the optimal system design in relation to panel height. Below table demonstrates the differences in the yield of fig trees across various heights of PV panels placed.

26 By assuming DC to AC ratio as 1.15, https://iea-pvps.org/wp-content/uploads/2023/10/National-Survey-Report-of-PV-Power-Applications-in-China-2022-%EF%BC%881017%EF%BC%89.pdf

27 Considering inter row distance of 2.6 m, and additional 50% space requirement, 1 kWp project would require project area of 15.3 m^2, hence 30.5 MWp of project can be installed on project area of 4,66,700 m^2

28 https://globalsolaratlas.info/map?s=31.620161,119.180103&m=site&c=31.620161,119.180103,11

29 CUF is metric used to evaluate the performance of a power project and is defined as the ratio of the actual output of a power project over a year to its potential maximum output if it operated at full capacity continuously over the same period.

30 LER is metric used commonly in agriculture sciences to evaluate efficiency of land use. LER for solar PV project is the ratio of energy generated from Agriphotovoltaics project and energy generated from conventional ground-mounted solar PV project. Combined with LER for agricultural yield, we will get total LER for the Agriphotovoltaics project.

Table 10: Height of panel vs crop yield

Height of the Panels (in m)	Difference in Yield of the Fig Trees[31]
2.5	19.8% ↓
3.2	30.2% ↓
3.9	48.8% ↓

Further, it was observed that the photosynthetic performance of fig leaves is consistent across various panel heights signifying no differences in the morphological features.

D. Inferences

The following are the key inferences drawn from the case study by the project team:

- **Project design:** The utilization of concrete piles as columns for the PV panels, in lieu of mild steel columns, is inferred to provide the requisite structural support for the elevated structure, which features a ground clearance of 3.2 meters and a tilt angle of 24°. The AgriPV project structure is exposed to substantially higher wind-induced structural loads compared to conventional ground-mounted solar PV systems, which at the same tilt angle typically have a ground clearance of 0.6 meters and can be adequately supported by mild steel columns.
- **Project capacity:** The AgriPV project implements an inter-row spacing of 3.2 meters, which is greater than the typical 2.6 metres[32] employed in conventional ground-mounted solar PV projects. This increased inter-row spacing reduces the number of modules that can be accommodated within the AgriPV project area. Consequently, the overall capacity that could be installed within the project area is approximately 32.5% higher than the current AgriPV project capacity.
- **Project operational parameter:** The PV operational characteristics of the AgriPV project are comparable to those of a conventional ground-mounted solar PV project. The Capacity Utilization Factor (CUF) on the AC side for the AgriPV project is approximately 13.7%, whereas a hypothetical ground-mounted solar PV project at the same location would exhibit a CUF of 15.3%.
- **Effect of Light Intensity on the yield of crop:** The results showed that the available light in the area between the inter-row spaces of the panels was in the range of 54.1%–67.1% relative to fully exposed areas, which was in turn 2.1 to 3.2 times that in the area under the panels. The available light in the area between the panels decreased as the height of the PV panels increased, with a reduction of 13.0% in comparison to the open field scenario, while the opposite trend was observed in the area under the panels, with an increase of 4.7%. The effective growth of crops is closely tied to the availability of light.

The Jiangsu (China) case study provides valuable insights into the practical application and design considerations of dual-land use systems. Specifically, the research highlights the trade-off between energy production and crop yield inherent in AgriPV designs. The elevated PV structure, while necessary for accommodating fig trees and providing shade, resulted in wider row spacing and a consequent reduction in potential energy output compared to a conventional system. However, the system achieved a respectable capacity factor (13.7%), demonstrating the operational viability of Agripv. Crucially, the study underscores the impact of panel height on fig yields, with decreasing yields observed at increasing heights, emphasizing the need for optimized panel placement. The choice of shade-tolerant figs proved critical for successful intercropping, as their reduced light requirements align well with the partially shaded conditions beneath the panels. Therefore, this case study concludes that successful AgriPV implementation requires a site-specific approach, carefully balancing design parameters such as panel height and spacing with crop selection based on shade tolerance and local climatic conditions to maximize both agricultural productivity and energy generation.

31 The % difference is with respect to the average yield of fig trees in open field conditions in China (5475 kg/ha)
32 Based on height difference of lowest and highest point of PV array, solar elevation and azimuth angles during the peak sunshine hours on winter solstice (for northern hemisphere)



2.1.4 Rationale for Discrepancy in Chickpea yield

The readers may observe that CAZRI Jodhpur data records yield decreases for nearly all crops under the panels — mung bean −4.6%, moth bean −8.6%, cluster bean −11.8%, chickpea −6.6%, cumin −10.3%, isabgol −7.8%, with aloe vera and brinjal "significantly lower" — which appears to contradict the report's framing that shade-tolerant crops should hold or gain yield (e.g. the JAU Junagadh increases, and the Sagar case study naming chickpea/gram a "top-tier" crop expected to gain 10–20%).

The Logical Rationale based on our understanding

The governing principle: Shade does not help or hurt a crop in the abstract. Its net effect is the sum of two opposing terms: a cost (less light for photosynthesis) and a benefit (lower leaf temperature and evapotranspiration, hence conserved soil moisture). Apart from this, the soil type plays a significant role as well.

What the evidence shows, reconciled in Table 11 below:

Table 11: Crop Yield Responses to AgriPV Designs and Conditions at CAZRI Jodhpur and JAU Junagadh

Study / setting	Design & conditions	Crop-yield effect (crop only)	What it tells us
CAZRI Jodhpur — kharif (rainfed)	Dense fixed-tilt desert array (GHI 5.6–6.0 kWh/m^2/day); yields measured in the shaded inter-row.	Mung bean −4.6% (but +7.7% in the 2019 double/triple-row design); moth bean −8.6%; cluster bean −11.8%.	High-light desert legumes lose most under heavy shade; a better design turned mung bean positive.
CAZRI Jodhpur — rabi (IRRIGATED)	Same array; winter crops grown under full irrigation.	Chickpea −6.6%; cumin −10.3%; isabgol −7.8%.	With water non-limiting, the moisture benefit is switched off and only the light cost remains — losses are the expected result.
JAU Junagadh	7.2 kWp elevated structure explicitly designed to MINIMISE shading; shade-tolerant tomato.	Tomato +150%; water-use e iciency +152% (cucumber), +60% (cherry tomato); land equivalent ratio up to 1.65	Light-managed design + shade-tolerant crop + microclimate/water benefit → gains.

Why the CAZRI figures read low – Potential Drivers

Table 12: Factors Influencing Crop Yield Differences in CAZRI and JAU AgriPV Systems

Driver	How it explains the CAZRI figures
Shading intensity / design	CAZRI used a dense, fixed-tilt array and reported the shaded inter-row; JAU Junagadh's structure was computer-designed to minimize shading. Same crop, very different light — hence opposite signs.
Water regime	CAZRI's chickpea, cumin and isabgol figures are explicitly from a fully irrigated rabi season. Shade's benefit is moisture conservation; with irrigation removing water stress, only the light cost is left, so a decline is expected.
Soil Type	• **Sandy Soil (like CAZRI's):** With low water retention, especially when irrigated, the moisture-saving benefits of shade are minimal. Shade is primarily a cost due to reduced light. • **Clay Soil (Vertisols):** These soils hold water well. Shade reduces evaporation and prevents soil cracking, a major cause of water loss in these soils. This leads to real water conservation, making shade highly beneficial for rainfed crops.



2.2 Global AgriPV Project Case Studies

GLOBAL AGRIPV PROJECT CASE STUDIES

2.2.1 Case Study I - Gabersdorf, Austria AgriPV Project

A. Brief of the Project

Josef Gründl, with a background in agriculture, and Peter Gsell, an expert in electricity, collaborated with Next2Sun to develop a 2 MWp AgriPV project in Gabersdorf, Austria. The system features (Table 13) vertically mounted bifacial solar panels with crops grown in the spaces between the rows of modules, maximizing land use efficiency. Covering over 5 hectares, the project generates over 2 GWh annually. The key features of the project site are given in the following table.

Table 13: Key features of the Gabersdorf, Austria AgriPV Project by Next2Sun

Given Parameters	Details
System Capacity	2 MWp
Commissioning year of the project	2023
Location of the project	Gabersdorf, Austria
Land Area of the project	51,000 m^2
Crops Cultivated	Pumpkin
SOME OTHER PARAMETERS	**DETAILS** [33]
Climatic Zone	Temperate
Average annual sunshine duration	5.2 hours per day
Average annual rainfall	1,000 mm
Average annual temperature	11° C
Soil Texture	Calcareous, with patches of alluvial and coastal saline soils[34]

33 Climate data
34 European Soil Bureau

a. Climatic Zone Overview of Project

Gabersdorf, Austria is located within a cool temperate humid climate zone. The region has a moderate climate with steady rainfall throughout the year, ranging from 800 to 1,200 mm annually. This means it experiences four distinct seasons, Spring, Summer, Autumn and Winter with a warmest month that averages below 72°F (22°C) and at least four months with average temperatures above 50°F (10°C).

b. Crop Overview/Agricultural Overview

Scenario of Crop Cultivation in Gabersdorf, Austria

The climatic conditions of Gabersdorf, Austria supports various types of farming, including vineyards, grains, and vegetables, because of its good moisture levels and stable temperatures. Farming is possible year-round, though cold snaps, frost, and wet conditions mean farmers need to use weather-resistant techniques. Wheat, maize, barley, potatoes, sugar beets, apples are all widely cultivated in Austria, including the region of Gabersdorf. Minor crops, such as fruits, vegetables, herbs, and spices, are also cultivated, with a notable emphasis on grapes for wine production.

Crop cultivated in the AgriPV Project

In Austria, the cultivation of oil pumpkins, particularly in the eastern provinces of Styria, Burgenland, and Lower Austria, is thriving. Styria, known for its distinctive pumpkin seed oil, is a major center for oil pumpkin cultivation. The region's climate and soil conditions are well-suited for this specific variety of pumpkin, which yields high-quality oil. The current AgriPV Project features the cultivation of oil pumpkins between the rows of solar modules in around 90% of the project area. However, it is to be noted that detailed findings on the impact of AgriPV on pumpkin yields are not yet published, as the project is still recent.

RATIONALE FOR CROP SELECTION

Shade Tolerance & Yield Response:

Oil pumpkins, like many other major commercial crops, are generally considered to require abundant sunlight for optimal growth. This means they have a high "saturation point," meaning they need a lot of light to reach their full potential. When considering AgriPV with oil pumpkins, factors like the spacing between solar panels, the type of panel (transparency, etc.), and the specific pumpkin variety (some may be slightly more tolerant) could influence the level of shade and its impact. Slight level of shading during the vegetative and reproductive phase may pose a significant impact on the yield of the crop.

Water and Irrigation requirements:

The water needs of oil pumpkin plants vary depending on their growth stage. Young plants require less water than mature plants, especially during fruiting. The amount of shade provided by the solar panels can affect the temperature and humidity under the panels, potentially reducing water evaporation and irrigation needs.

Height and Growth Habit:

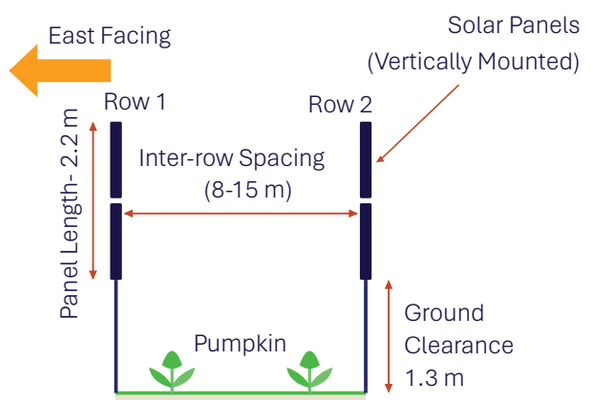
Oil pumpkin is a vining plant, meaning it spreads across the ground rather than growing upright like some other crops. In an AgriPV system, this sprawling habit can be accommodated by planting the pumpkin in rows or spaces between the solar panels.



c. Solar Photovoltaic Potential Overview

The solar modules are vertically mounted into multiple rows with one module stacked on top of another as illustrated below in Figure 11. The height of the mounting structure from the ground is kept at 1.3 m while inter-row distance is kept between 8 m and 15 m. Due to bifacial module used in the vertical setup, solar generation peaks twice a day, one during morning and another in the evening.

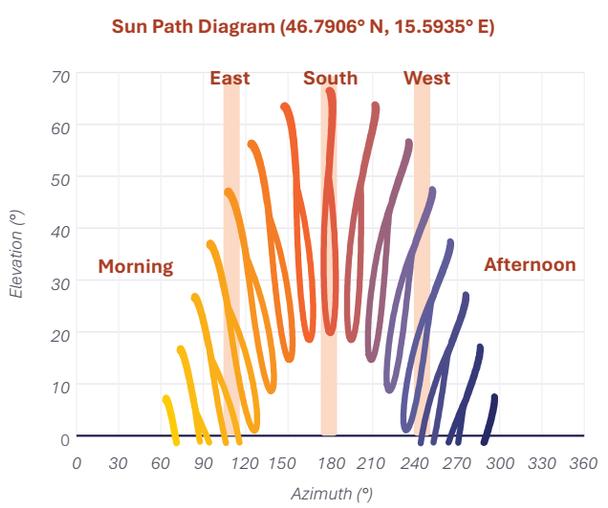
Figure 11: Specified PV structure design and system's architectural implementation within this AgriPV project.



For the project site, the sun path diagram has been plotted and presented in the adjacent Figure 12. The optimum tilt angle is based on maximizing the total solar irradiation received on a tilted surface throughout the year. According to Global Solar Atlas, the optimum tilt for south facing fixed tilt PV array in Gabersdorf is around 37^0.

The sun elevation angle can be considered from the sun path diagram. The peak sunshine hours (10 AM to 2 PM) and the winter solstice are considered for the elevation angle. In this case the elevation angle comes out to be 17.22 degrees.

Figure 12: Sun Path Diagram for the specified project Site





b. Comparative analysis of design aspects of AgriPV project with ground-mounted project

The performance of the AgriPV system can be evaluated based on its yield and the capacity utilization factor (CUF) of the project. This evaluation allows us to compare the AgriPV system (Table 14) with a traditional ground-mounted system, helping us understand the differences between an AgriPV system and a standard PV system. For estimating the power generation from the hypothetical project, the team has made use of the photovoltaic power potential provided over Global Solar Atlas at the project coordinates approximated as that of Gabersdorf, Austria. The project design of the hypothetical ground-mounted solar PV system follows common industry frameworks for such setups and has been mentioned in the below table. Considering the previously mentioned parameters, the comparative analysis between AgriPV system and ground-mounted system is as follows:

Table 14: Comparative analysis between AgriPV system and ground-mounted system with reference to Gabersdorf, Austria AgriPV Project by Next2Sun

Parameter	For AgriPV Project (Case Study)	For conventional ground-mounted solar PV (estimated)	Remarks
COMMON DESIGN PARAMETERS			
PV panel	Bifacial	Bifacial	Base parameters considered to be same.
Solar tracking	None	None, fixed tilt	
Tilt angle (degrees)	0	37°	
Material of PV panel columns, rafters, and purlins	MS Steel	Hot dip Galvanized Mild Steel	
Azimuth direction	South Facing	South facing	
Project Area	51,000 m^2	51,000 m^2	
DIFFERENT DESIGN PARAMETERS			
Ground clearance (lowest height of PV panel from ground)	1.3 meters	0.6 m	Significant design difference for allowing crop cultivation.
DC System Capacity	2.2 MWp	3.18 MWp[35]	Design difference allows more modules to be installed in ground-mounted PV project, hence capacity difference
COMPARISON OF PROJECT GENERATION			
Annual Generation per kWp	1100 kWh	1174.5 kWh[21]	The generation on unit capacity basis is lesser than ground-mounted PV project primarily due to a greater number of PV panels present in case of simple ground-mounted.
Capacity Utilization Factor (CUF on AC side)	12.55%	13.4%	
Annual Generation per m^2	47.45 kWh	50.66 kWh	The generation on unit land basis is significantly lower for AgriPV project.
Annual Energy Production	2200 MWh/year	2349 MWh/year	Overall generation is lower for AgriPV project due to lower installed capacity.

35 Considering inter-row distance of 0.8 m, and additional 50% space requirement, 1 kWp project would require project area of 16.4 m^2, hence 3.18 MWp of project can be installed on project area of 51,000 m^2

c. Inferences

The following are the key inferences drawn from the case study by the project team:

- **Effect of Wind Speed:** The vertical arrangement of solar modules in multi-row arrays acts as an effective wind barrier, protecting crops from strong winds and promoting undisturbed growth. This shielding also creates a safer environment for grazing animals.
- **Project Technology and Capacity:** In vertically mounted solar projects, the project capacity is usually lower as compared to the conventional tilted ground-mounted solar projects when considered the same land area. It is due to the increased shadow length that is made between two rows of solar panels. Therefore, the inter-row spacing of vertically mounted systems is usually higher to minimize the effect of shading. The loss in energy yield makes Vertical PV economically challenging. Thus appropriate use of technology to increase the energy yield and use appropriate capacity to balance out agricultural and solar energy needs to be make AgriPV viable and solar also economically viable
- **Potential Impact on Crop:**
  - Gabersdorf, Austria's temperate climate is suitable for pumpkin cultivation, although pumpkins require ample sunlight while being susceptible to excessive heat and water stress.
  - General AgriPV research suggests reduced water consumption and improved soil moisture under solar panels.[36] For pumpkins, this could mean reduced evaporation losses and heat stress, potentially enhancing growth and quality, especially during dry periods.
- **Shading Impact:** Given the vertical configuration of the solar panels providing more shading, yield of pumpkins are likely to be affected. Studies on other crops indicate that light-demanding crops like maize can be grown under AgriPV under certain conditions suggests that pumpkins, with similar light needs, could adapt similarly.[37]

This 2023 Austrian case study examines a 2 MWp AgriPV system in Gabersdorf, featuring vertically mounted bifacial panels and pumpkin cultivation. The system's design prioritizes land use efficiency, generating over 2 GWh annually on 5 hectares. A key inference is the wind-buffering effect of the vertical panels, creating a more favorable microclimate for crops and potentially livestock. This design also requires fewer structural components, reducing installation costs. However, the vertical orientation, while maximizing land use, necessitates wider inter-row spacing (8-15m) to minimize shading, resulting in a lower overall capacity compared to traditional systems. A comparable ground-mounted system on the same land could potentially reach 3.18 MWp. The bifacial panels, however, partially compensate for this by capturing light from both sides, leading to a respectable capacity utilization factor of 12.55%.

While detailed yield data for pumpkins is not yet available, the minimal land coverage (1%) by the vertical panels suggests limited shading impact. Furthermore, the system's potential to reduce water consumption and improve soil moisture aligns well with pumpkin cultivation needs in Gabersdorf's temperate climate, potentially mitigating heat and water stress. This case study demonstrates the potential of vertical AgriPV systems to efficiently combine energy and food production, particularly for crops suited to the created microclimate. Further research is needed to quantify the specific impacts on pumpkin yields and optimize system design for various crop types and climatic conditions. The project highlights the innovative potential of Agriphotovoltaics to address both energy and agricultural needs.

36 Source: [A multidisciplinary view on Agriphotovoltaics: Future of energy and agriculture] (https://www.sciencedirect.com/science/article/pii/S1364032124002387))

37 Source: [Agriphotovoltaics, a promising new tool for electricity and food production: A systematic review] (https://www.sciencedirect.com/science/article/pii/S1364032123011358))

GLOBAL AGRIPV PROJECT CASE STUDIES

2.2.2 Case Study II - Enugu, Nigeria AgriPV Project

A. Brief of project:

The AgriPV Project was set up in the Centre for Energy Research and Development, University of Nigeria, Nsukka, Enugu State, Nigeria (6°51'57''N 7°24'57''E) in 2022 with a capacity of about 20 kWp. The objective of this project was to investigate the effect of AgriPV system on microclimate, photosynthesis, and agronomic performance of mungbean in a tropical environment. This study is one of the first in tropical sub-Saharan Africa to show that AgriPV systems improve crop yield and resilience and enable renewable energy generation on farmland without sacrificing food production. The brief of the project is given in the below Table 15

Table 15: Key features of Centre for Energy Research and Development, University of Nigeria, Nsukka, Enugu State, Nigeria AgriPV Project

Parameter	Value
System Capacity	20 kWp
Commissioning year of the project	2022
Land Area of the project	205.8 m^2
Solar tracking	None
Climatic Zone	Tropical savanna climate
Tilt angle	20° (EPV and WPV)
Ground clearance (lowest height of PV panel from ground)	2.65 to 3.15 meters
PV panel	Poly C-Si, 265 W rated
PV array dimensions	21 x 9.8 m
Crop Cultivated	Mung Beans

a. Climatic zone overview

According to the Köppen climate classification, Nsukka, Enugu, Nigeria falls under the tropical climate. This classification is characterized by a wet and dry season, with higher rainfall during the summer and a drier period during winter. The region experiences a generally warm climate throughout the year, with distinct wet and dry seasons. Nsukka has mean annual rainfall of 1276±706 mm, solar radiation of 1452±269 w m^2, and temperature of 32±5°C16. Relative humidity varies due to seasonal variations during the rainy and dry seasons. The upper limit (about 89%) is usually experienced during the peak rainy season (July to August) while the lower limits (39–41%) occurs during dry spells (December and January).

b. Crop/Agricultural Overview:

Scenario of Crop cultivation in Enugu, Nigeria

Enugu State, located in southeastern Nigeria, is known for its agricultural production, particularly in the cultivation of major staples and livestock rearing. The agricultural landscape is influenced by the region's climate, which is characterized by a tropical rainforest pattern with a distinct wet and dry season. The major crops included Yam, Cassava, Rice, Maize etc., and the minor crops included oil palm, plantains, bananas, vegetables for local consumption etc.,

Crop cultivated in the AgriPV Project

In this research it is studied, how placing solar panels above crop fields affects the growth of mung bean (Vigna radiata), a key legume crop in many parts of the world, particularly in tropical Nigeria where high temperatures and intense sunlight can stress crop growth. To study this process, an experimental setup was created by the researchers where five mungbean genotypes namely, Tvr18, Tvr28, Tvr65, Tvr79 and Tvr83 were grown under three AgriPV treatments as described below.

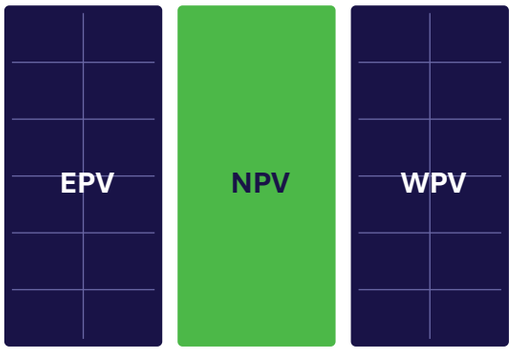
1. Open-field – exposed to full sunlight (NPV- No PV)

2. AgriPV system- shaded by solar panels (under this system they are further bifurcated into configurations) One with panels facing east (EPV) and another with facing west (WPV)

c. Solar PV Project Design Overview

As seen in Figure 13, three configurations of solar module placements can be clearly seen divided into 3 types; first one where the modules are east-west faced (EPV), second where no solar modules (NPV) are used and taken as reference for conventional agriculture setup and third, where modules are placed west-east facing (WPV). In EPV and WPV bifacial solar modules were installed, and the plot was covered with a transparent acrylic glass material for unrestricted solar transmittance. The solar modules were mounted at the height ranging between 2.65 m to 3.15m. The crop yield is studied under these three configurations to understand the optimal module orientation and land utilization factor.

Figure 13: Three configurations of solar module placements considered



B. Impact on Crop Performance in the AgriPV Project

Mungbean requires adequate sunlight throughout its growth period to maximize photosynthesis, biomass accumulation and ultimately seed yield. Although a few studies have shown that shading can negatively influence various physiological growth processes including photosynthesis, respiration and nutrient assimilation, the extent of these effects depend on the degree and duration of shading.

In the experimental plot, seeds were sown in 10 L Pots prefilled with inert coconut fibre dust and placed at a spacing of 40 × 40 cm. Two seeds were sown per pot and later thinned down to one-seed at 1 week after planting. Universal orange fertilizer[38] was applied at the rate of 2 g/l or 20 g per pot.

This research has demonstrated the impact of AgriPV systems on microclimate, photosynthesis, growth and yield performance of Mung Bean. Mini-PAM II Photosynthetic Yield Analyzer (WALZ, Germany) was used for determination of leaf temperature, relative humidity, photosynthetic active radiation (PAR), and photosynthesis variables. Below table demonstrates the impact of different parameters across PV experimental designs in comparison to open field conditions (NPV).

Table 16: Impact of different parameters across PV experimental designs in comparison to open field conditions (NPV) at Centre for Energy Research and Development, University of Nigeria, Nsukka, Enugu State, Nigeria AgriPV Project

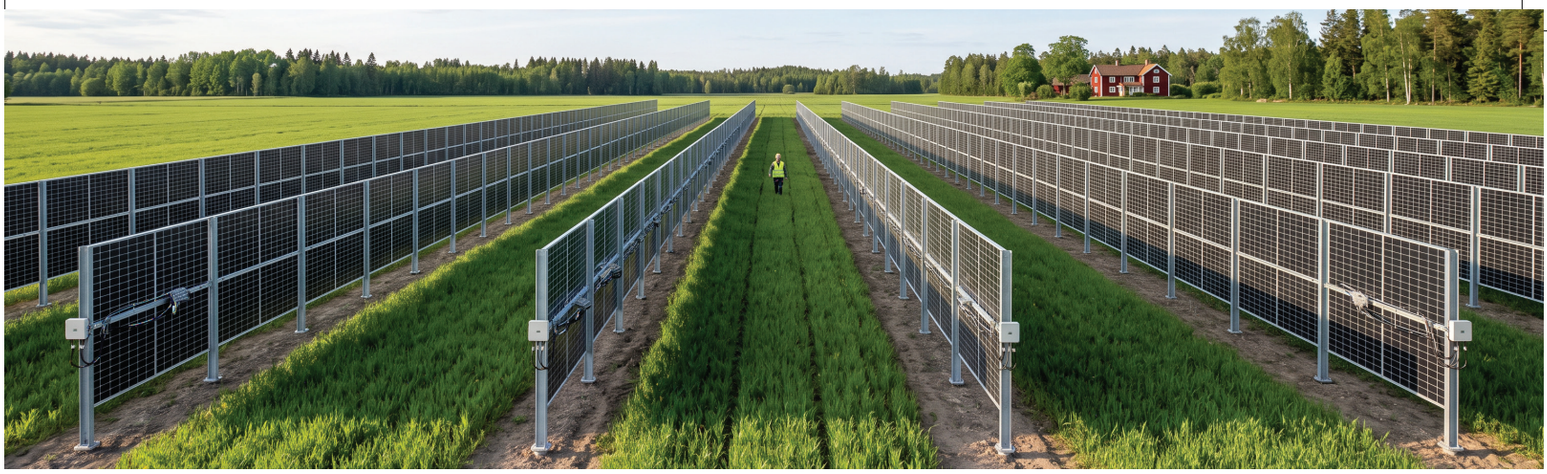
Key Parameters	EPV	WPV
Photosynthetic Active Radiation (PAR)	5-42% ↓	22-47% ↓
Leaf Temperature	3-5% ↓	6-9% ↓
Leaf Relative Humidity	3-6% ↑	3-8% ↑
Delayed Flowering	6 days	10 days
Delayed Podding	9 days	11 days
Plant Height	2-9% ↑	3-14% ↑
Leaf Number	10-13% ↑	21-42% ↑
Pod Number	28% ↑	24% ↓
Seed Number	25% ↑	31% ↓
Seed Weight	38% ↑	28% ↓

38 (N-16%, P2O5–5%, K2O-25%, MgO-3.4%, Fe-0.10%, Mn-0.04%, B-0.01%, Cu-0.01%, Mo-0.001%, Zn-0.01%)

C. Inferences

- **Impact of Shading on PAR, Temperature and Relative Humidity:** Results showed that PV shading significantly reduced PAR and leaf temperature while increasing relative humidity compared to non-PV shading. This cooling and humidifying effect, attributed to the opaque PV modules blocking 5-47% of incident radiation, led to temperature reductions of 3-9% and humidity increases of 3-8%. The orientation of the PV panels also played a crucial role, with east-west oriented panels (EPV) exhibiting higher PAR and temperature, and lower relative humidity compared to west-east oriented panels (WPV), likely due to the sun's east-to-west path. Overall, the findings emphasize the importance of considering panel orientation when installing AgriPV facilities to optimize the microclimate for plant growth.
- **Impact on Phenology (Flowering, podding etc.,):** Mungbean phenology (developmental stages) was most delayed under west-east oriented PV panel shading (WPV). The delay in phenology due to PV shading is linked to changes in microclimate parameters like PAR, temperature, and relative humidity within the shaded environment, aligning with previous findings on the impact of shading on plant development and bloom timing.
- **Impact on Yield:** AgriPV systems significantly impacted mungbean growth. Under west-east oriented PV panels (WPV), mungbean plants were taller and thinner, typical of plants under shade trying to maximize light exposure (etiolation), resulting in more leaves but with smaller sizes. East-west oriented PV panels (EPV) resulted in superior pod and seed production due to improved microclimate conditions allowing higher photosynthetic efficiency. Further, mungbean crops grown under EPV had significantly more pods and seeds per plant and non-significantly higher seed yield compared to the un-shaded control, marking a breakthrough in AgriPV research.
- **Impact of Orientation on Solar Generation:** The solar generation was more in WPV configuration than EPV configuration. In the given region, the solar irradiation was maximized when the panels were placed with West oriented with a tilt of 20 degrees.





2.2.3 Case study III - Vastmanland, Sweden (Vertically Mounted) AgriPV Project

A. Brief of the Project

This case study on an AgriPV project[39] in Västmanland, Sweden is based on research conducted by Mälardalen University (MDU) in collaboration with institutions as the County Administrative Board of Skåne. The analysis is entirely based on two simulation models: PVsyst, used to evaluate solar energy generation, and Environmental Policy Integrated Climate (EPIC), applied to assess crop yield. A simulation model was built based on the physical pilot project of 22.8 KW AgriPV system for evaluating the impact of change in inter-row distance between the solar modules on crop yield.

The case study also aims to determine the ideal inter-row distance between solar modules that optimizes both crop yield and solar energy production, while assessing the viability of the AgriPV project. The viability of the AgriPV project is mostly determined through LER[40] that is the key performance indicator for combining agriculture and solar generation on the same land. The key features of the project site are given in the following table.

Table 17: Key features of Mälardalen University (MDU) AgriPV Project in Västmanland, Sweden

Given Parameters	Details
System Capacity	22.8 kW
Commissioning year of the project	2020
Location of the project	Vastmanland, Sweden
Climatic Zone	Continental
Crops cultivated	Potato, Oats
OTHER PARAMETERS	**DETAILS**
Average annual sunshine duration	1829 hours
Average annual precipitation	654 mm
Average annual temperature	7° C
Soil Type	Clay, sand, silt, and moraine deposits (Ballasted mounting structures are preferred)

39 Optimization of Vertically Mounted Agriphotovoltaics System

40 LER is a metric used to evaluate the efficiency of combining agriculture and solar power generation on the same land. It compares the productivity of a dual-use system (where crops and solar panels coexist) to the productivity of separate land use for farming and solar energy.

a. Climatic zone overview of the site

The project site falls primarily within the cold, humid continental climate with warm summers, with some areas transitioning to a temperate oceanic climate in the southern parts. The average annual sunshine duration is 1829 hours, and the annual precipitation is 654 mm, distributed evenly throughout the year, with slightly higher amounts in late summer[41]. The mean annual temperature is 7°C and snow cover lasts from December to March.

b. Crop overview/Agriculture overview

Scenario of Crop Production in Vastmanland, Sweden

Västmanland has cold humid continental climate with distinct seasons. Summers are relatively mild, with average temperatures around 15-20°C, while winters are cold, with temperatures often dropping below freezing. The growing season is typically from late spring to early autumn. The crop cultivation is generally characterized by a mix of cereal production (barley, oats, wheat), grasslands, and some vegetable and fruit growing.

Crops cultivated in the AgriPV Project

In the pilot project, pasture grass and clovers were cultivated due to the availability at the project site. However, for the case study, researchers selected different crops like potato and oats for simulation. Potato, being shade-tolerant, and oats, being shade-intolerant, provided contrasting conditions, making them suitable for analysing yield variations in a vertically mounted system where shading plays a crucial role.



RATIONALE FOR CROP SELECTION

Shade Tolerance & Yield Response:

Potatoes are considered shade-tolerant and can be grown under AgriPV systems with minimal yield reduction, especially when shading levels are moderate. Studies show that shading up to 50% of solar irradiance has minimal impact on potato yields. However, excessive shading (RSR > 50%) can negatively impact potato growth and yield. In certain situations, shading can even lead to increased yields, particularly in hot and dry environments. A Study by Weselek et al. (2021) showed that shading from PV modules had a positive effect on organically grown potato yields, with harvests increasing by up to 11% compared to the unshaded control. This is likely due to the reduced water stress and lower soil temperatures under the shade. Oats generally tolerate up to 50% shade, and some varieties can even tolerate up to 60% shade. Beyond 60%, yield and maturity can be affected.

Water and Irrigation requirements:

Oats are relatively drought tolerant Shading from solar panels can lower water demand, as it reduces evapotranspiration (water loss from plants and soil). In case of Potato, water savings under AgriPV can range from 14-29% in evapotranspiration, with potential irrigation water savings of up to 20%.

Height and Growth Habit:

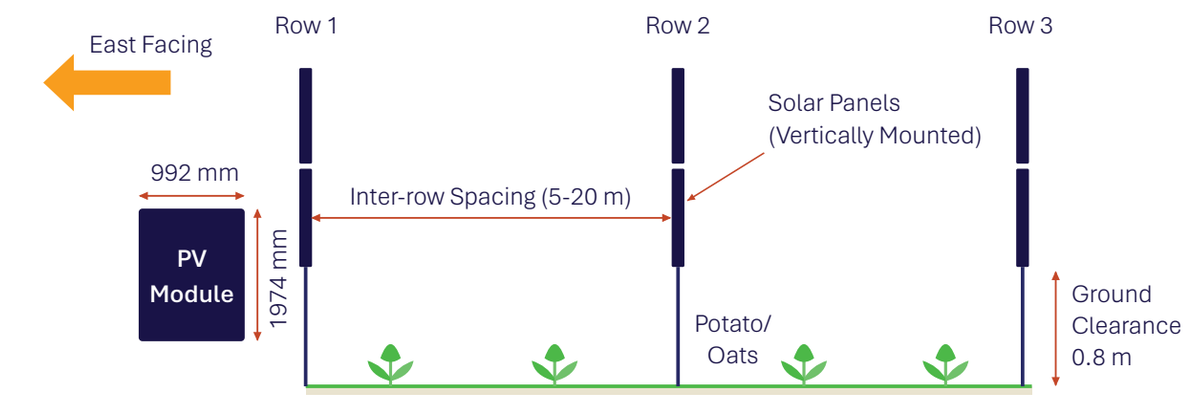
Studies have shown that potato plants cultivated under AgriPV systems (AV) exhibit a notable increase in plant height, sometimes almost twice as tall as those grown in open fields. This growth response is attributed to the partial shade provided by the solar panels, which can reduce light intensity and stimulate upward growth. Oats, in general, can grow to a height of 1.8 meters. However, under AgriPV, the reduced sunlight due to the solar panels may cause oats to grow shorter than their natural potential.

41 Vastmanland Climatic overview

c. Solar photovoltaic potential overview

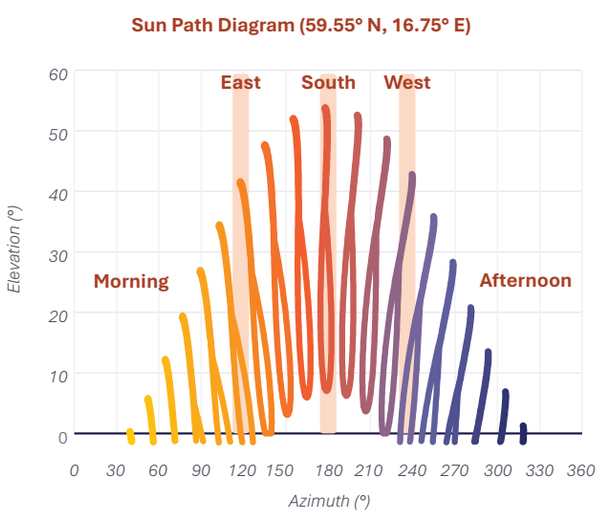
The design of the pilot project was based on a solar fence system, where solar panels were vertically mounted in two rows surrounding the land area to form a fencing on the agricultural land. The same design was used in the simulation model by making some alterations in the layout as shown in figure below. In the simulation model, the researchers considered the design where solar modules are vertically mounted in three rows, and each row is further divided into two individual rows stacked on top of each other. Each individual rows consists of 10 modules. The impact on crop yield was then studied, by adjusting the spacing between solar module rows varying from 5m to 20m.

Figure 14: Specified PV structure design and system's architectural implementation within this AgriPV project.



For the project site, the sun path diagram has been plotted and presented in the adjacent figure. The optimum tilt angle is selected at which solar irradiation falling on the solar panel surface is maximized throughout the year. According to Global Solar Atlas, the optimum tilt for east facing fixed tilt PV array in Vastmanland is around 44^0.

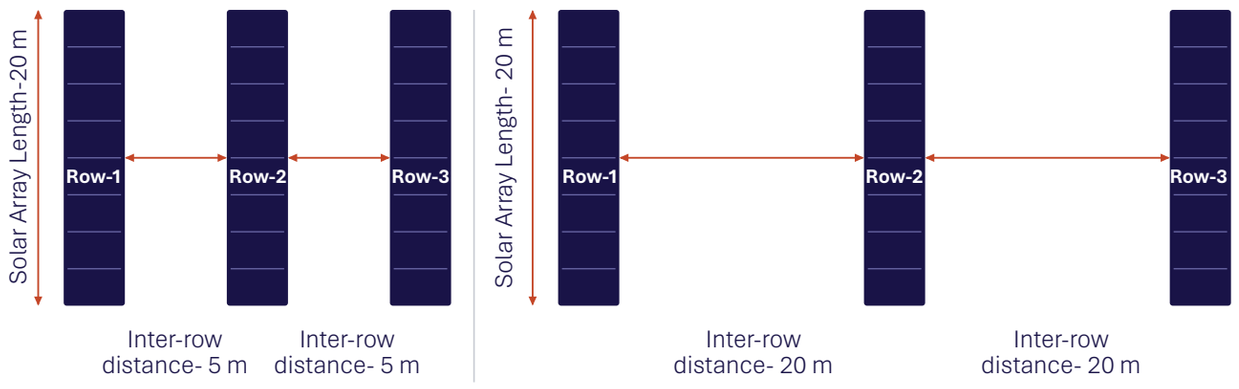
Figure 15: Sun Path Diagram for the specified project Site



The sun path diagram has been used to calculate the minimum inter-row spacing required between two PV arrays to avoid impact of shading for a simple ground-mounted solar project at Vastmanland.

To calculate inter-row spacing, the sun elevation angle can be extracted from the sun path diagram. The peak sunshine hours (10 AM to 2 PM) and the winter solstice are considered for the elevation angle. In this case the elevation angle comes out to be 5.2 degrees. Considering the height difference of 0.6 m between the lowest point of PV array and the ground depicted in the diagram above, the minimum inter row spacing between the two PV arrays should be around 5.6 m.

Figure 16: Configuration cases; first when inter row distance between the solar modules is 5 meters and another with 20 meters the layout.



B. Comparative analysis of design aspects of AgriPV project with ground-mounted project

For comparing the AgriPV project, a hypothetical ground-mounted solar project is referred at the same location for reference. It is done to understand the difference in design parameters of an AgriPV system when compared to a conventional ground-mounted system keeping the solar capacity constant.

Assumptions taken for comparison: The design parameters of the AgriPV project are taken from the case study referred while conventional ground-mounted project design parameters are calculated making following assumptions.

- The kWh/year value for a conventional solar project is sourced from the Global Solar Atlas.
- The capacity of the hypothetical ground-mounted solar project is taken the same as AgriPV. With this parameter constant, other parameters are calculated accordingly.
- The land area considered for conventional ground-mounted is considered 16 m^2 per kW.

The system parameters for both the AgriPV and ground-mounted system are as follows:

Table 18: Comparative analysis of design aspects of AgriPV project with reference to ground-mounted project Mälardalen University (MDU) AgriPV Project in Västmanland, Sweden

Parameters	AgriPV Design	Ground Mounted System	Remarks
COMMON- DESIGN PARAMETERS			
System Capacity	22.8 kW	22.8 kW	Base parameters taken as constant to derive the output parameters.
Azimuth Direction	East Facing	East Facing	
PV Panel	Bifacial	Bifacial	
Module Dimension	1974 ×992 mm	1974 ×992 mm	
Solar Tracking	None	None	

Table 18: (continued) Comparative analysis of design aspects of AgriPV project with reference to ground-mounted project Mälardalen University (MDU) AgriPV Project in Västmanland, Sweden

Parameters	AgriPV Design	Ground Mounted System	Remarks
DIFFERENT- DESIGN PARAMETERS			
Orientation & Tilt angle	Vertical fixed, 90^0	Horizontal, 43.14^0	Tilt angle for conventional ground-mounted project is 43.14^0 using Global Solar Atlas
Ground clearance (lowest height of PV panel from ground)	0.8 m	0.6 m	AgriPV project needs more ground clearance to accommodate crops.
Interrow spacing	Potato- 8.5m Oats- 9m	5.6 m	Inter row spacing is calculated using sun path diagram and tilt is 43.14^0.
Total Land Area	200 m^2 and 800 m^2 for 5m and 20 m respectively.	364.8 m^2	The land area required for AgriPV is almost double as compared to ground-mounted system.
Annual Energy Production	14,873 kWh/year	22,789 kWh/year	Increase in solar generation for ground-mounted system, as a greater number of modules can be installed in ground-mounted project.
COMPARISON OF PROJECT GENERATION			
CUF (%)	7.44	11.41	AgriPV projects have less CUF than ground-mounted projects.
Land Equivalent Ratio	1.2	1	LER >1, shows the better land utilization in AgriPV project.
Annual Generation per m^2	24.78 kWh	62.46 kWh[42]	The land utilization in AgriPV project is 2.5 times less compared to conventional ground-mounted system.
Annual Generation per kWp	652.32 kWh	999.5 kWh	

C. Impact on Yield of crops cultivated in the AgriPV Project

The research provides a sensitivity analysis that evaluates the relationships between crop yield, specific electricity production, and mutual row distance in an AgriPV setup. By varying the row distance from 5 to 20 meters, it was observed that crop yield, specifically for oats and potatoes, nearly doubled. Maximum yields in open fields without shading were recorded at 5.0 t/ha for oats and 6.9 t/ha (dry matter) for potatoes, while regional statistics in Västmanland and Örebro Counties provided averages of 4.89 t/ha and 36.74 t/ha (7.4 t/ha dry matter) respectively. Below table demonstrates maximum and minimum yields recorded by Potato and Oats at the row distance of 5 to 20m.

Table 19: Impact on Yield of crops cultivated at Mälardalen University (MDU) AgriPV Project in Västmanland, Sweden

	Variances in Yield (t/ha) across row distances		
Major Crops	**5m**	**12m**	**20m**
Potato	3.5	5	6
Oats	3	4	4.5

42 Global Solar Atlas

D. Inferences

Simulations were conducted by researchers across a range of row distances to identify the optimal LER and annual electricity production. Based on the analysis conducted in this case study, the following inferences can be drawn:

- **Project Design-** In a vertically mounted system (fence-type[43]), the number of solar modules that can be installed on the AgriPV project land remains nearly fixed, leading to a plateau in PV generation. However, agricultural yield can be enhanced by widening the inter-row spacing between solar modules, allowing for more crop cultivation in the available area. Therefore, in a fence-type AgriPV system, the total LER of the project can only be improved by increasing the agricultural LER, as the PV LER remains constant.
- **Impact of Geographical Factors on Inter-row Distance-** In countries like Sweden, where the elevation angle is low (less than 10^0) the inter-row distance required between the solar modules is very high compared to countries with higher elevation angles.
- **Correlation between inter-row distance and yield:** It is inferred from the above study that in an AgriPV system, the relationship between crop yield and row distance is crucial. The optimal row distances, considering a Land Equivalent Ratio (LER) above a certain threshold like 1.3, are 8 meters for oats and 7 meters for potatoes in open field conditions. However, if the target is to ensure 70% of the crop yield as compared to open field conditions, the row distance needs to be increased to 9 meters for oats and 11 meters for potatoes. This increase in row distance results in a decrease in LER but is necessary to maintain a substantial portion of yield when integrating solar panels into the agricultural framework.
- **Optimization of LER and Energy Production** Simulations conducted in the case study using PVsyst helped determine the ideal inter-row spacing for maximizing both crop yield and annual energy generation. The study found an LER value of 1.2, demonstrating that vertically mounted AgriPV systems using bifacial PV modules can enhance land use efficiency by simultaneously producing food and electricity. Since the LER value is greater than one, we can infer that the AgriPV project demonstrates feasibility.

This case study investigates the optimal design of a vertical AgriPV "solar fence" system in Västmanland, Sweden, focusing on oat and potato cultivation. A key finding is the significant impact of inter-row spacing on crop yields. Increasing the distance from 5m to 20m nearly doubled yields for both crops, highlighting the sensitivity of these crops to shading in this low sun elevation environment. While wider spacing improves agricultural output, the vertically mounted design limits the total installable PV capacity, meaning energy generation plateaus even as land use efficiency increases. Consequently, optimizing system design requires balancing crop yield with energy production. The study identifies optimal row distances of 8m for oats and 7m for potatoes to achieve a Land Equivalent Ratio (LER) above 1.3. However, maintaining 70% of open-field yields necessitates wider spacing (9m for oats, 11m for potatoes), albeit with a lower LER. The achieved LER of 1.2, exceeding 1, validates the viability of the AgriPV approach in this context. This study demonstrates the potential of vertically mounted, bifacial PV AgriPV systems to enhance land use efficiency in regions with low sun elevation but underscores the need to carefully consider row spacing to balance the competing demands of crop production and solar energy generation. The findings provide valuable insights for optimizing AgriPV system design in similar temperate climates.

43 A solar fence type Agriphotovoltaics system (or vertical Agriphotovoltaics) uses vertically installed, bifacial solar panels in East-West rows. This setup enables dual land use for agriculture (crops or grazing) between the rows while generating electricity from morning and evening sunlight.

2.2.4 Case Study IV - Isinya, Kenya AgriPV Project

A. Brief of project

The AgriPV project in Kenya is situated at Latina Agribusiness Solutions (LAS) in Isinya, Kajiado County. This system has been designed to align with the site's electricity demand and is connected to the grid to help supplement the existing power supply.

The key features of the site are given in the following table:

Table 20: Key features of the Isinya, Kenya AgriPV Project

Particular	Details
System Capacity	62.1 kWp
Commissioning year of the project	2022
Location of the project	Latina Agribusiness Solutions (LAS), Isinya
Land Area of the project	800 m^2
Climatic Zone	Hot semi -Arid
Crops cultivated	Cabbage, Onion, Coriander, and Kale.
OTHER PARAMETERS	**DETAILS**
Average sunshine duration	7.5 hours per day
GHI	5.4 kWh / day
Average annual rainfall	687 mm
Average annual temperature	19.1 degree Celsius[44]
Soil Type	Clayey soil
Soil Texture	gypsum, silicified lithics, and limestone

a. Climatic zone overview of the project

Isinya, located in Kajiado County, Kenya, falls within the hot semi-arid, Köppen climate zone, characterized by low rainfall, high temperatures, and a distinct wet and dry season. This classification is based on regional climate data and agro-ecological zoning studies for Kenya, particularly those referencing Kajiado's semi-arid lowlands.

Annual precipitation ranges from 500–700 mm. The moisture index is less than 50%, typical of Kenya's Agro-Climatic Zone V (semi-arid), as per the Kenya Soil Survey (2010). Rainfall is erratic, often insufficient for rainfed agriculture without supplementary irrigation. Mean annual temperatures range from 18–30°C. The length of the growing period (LGP) is 90–120 days, limited by moisture availability, making drought-tolerant crops critical. Evapotranspiration often exceeds rainfall, necessitating water conservation techniques like rainwater harvesting or drip irrigation.

Isinya's semi-arid climate is part of Kenya's broader arid and semi-arid lands (ASALs), which cover ~80% of the country's land area and are prone to periodic droughts, as noted in FAO's Kenya overview. The region's soils, primarily sandy loams and vertosols, have low fertility and limited water-holding capacity, further constraining agricultural potential. However, the soil at Latia Agribusiness Solutions in Isinya is primarily volcanic and fertile, rich in minerals and ideal for various agricultural practices. Volcanic soil is formed from volcanic ash and lava, making it rich in minerals and nutrients.

44 https://www.sciencedirect.com/science/article/pii/S1364032124007925

b. Crop overview/Agricultural overview

Scenario of Crop Cultivation in Isinya, Kenya

Isinya's agricultural landscape is dominated by smallholder farming and pastoralism, with crop production constrained by the BSh climate's low rainfall and high evaporation rates. The major crops grown are drought tolerant, have short growth cycles, and highly suitable for semi-arid conditions. These include maize, beans, cowpeas, green grams (mung beans), and tomatoes, with some horticultural crops like onions and kale grown under irrigation. Kajiado's total arable land is limited (18% of Kenya's land).

Isinya's farming is primarily rainfed, with smallholder schemes using water harvesting or shallow wells for irrigation. Intercropping (e.g., maize with beans or cowpeas) is common to maximize land use and reduce risk. The BSh climate favours drought-tolerant crops like green grams, cowpeas, and beans, which require 400–600 mm rainfall and tolerate high temperatures. Maize is less ideal but widely grown due to its staple status, with irrigation mitigating moisture deficits. Tomatoes thrive under irrigation, leveraging Isinya's proximity to Nairobi for market access. The BSh climate's low rainfall (500–700 mm) and high temperatures (18–30°C) favour drought-tolerant crops like coriander and kale, which require minimal water. Cabbage and onions, while water-intensive, are viable with irrigation, leveraging Isinya's warm climate and proximity to markets. The short growing season (90–120 days) supports quick-cycling vegetables, aligning with the bimodal rainfall pattern.

Crop Cultivation in Latia Agribusiness Solutions in Isinya

The crops produced in Latia Agribusiness Solutions in Isinya, Kenya were cabbage, onion, coriander, and Kale. At LAS, Wuxal foliar NPK fertilisers and pesticides were applied as per LAS' crop management strategy. The rainwater harvesting system at lower edges of the PV panels channels rainwater and panel cleaning water runoff into the tankers (with capacity of 10000 L) supplementing the existing centralised irrigation systems during periods of water scarcity.

RATIONALE FOR CROP SELECTION

Shade Tolerance & Yield Response:

Cabbage, kale, and coriander thrive in the partial shade (50% panel density) provided by AgriPV systems. Kale achieves higher yields in cooler microclimates, while coriander benefits from shade, maintaining quality in hot conditions. Onions perform stably with the aid of irrigation services.

Water Use Efficiency & Climate Resilience:

The shade from the AgriPV system reduces evapotranspiration, leading to about a 15% decrease in irrigation needs. Kale and coriander thrive on limited water availability. Cabbage and onions, while more water-intensive, benefit from the project's water-saving features (Rainwater harvesting), making them suitable for intensive farming in Isinya's BSh climate.

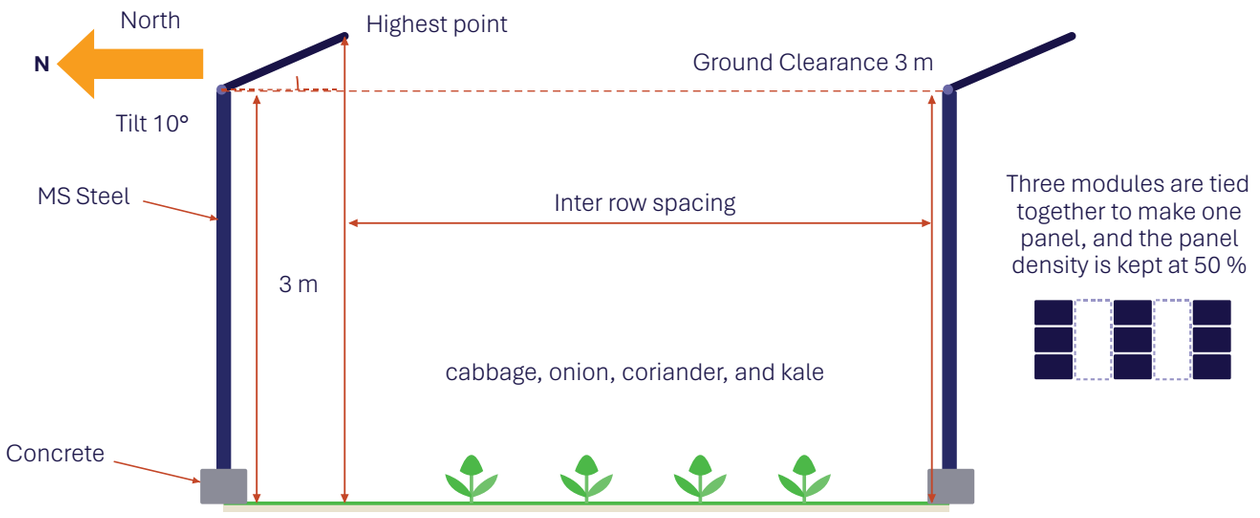
Suitability for Small-Scale Plots:

It seems that this project prioritized high-density crops with short growth cycles. Cabbage, kale, and coriander are well-suited for testing AgriPV viability within Isinya's rainfall pattern. Their compact growth is ideal for easy farm operations.

c. Solar photovoltaic potential overview

The AgriPV system described in the research article, has 180 modules (each panel- 345 W) with a total surface area of 40*20 m (800 m^2). The panels are tilted at an angle of 10 degrees towards the north. A tilt of 10 degrees was selected to prevent soiling and allow water runoff. The bottom edge of the panel is positioned 3 meters above ground level, and the PV arrays are mounted on a steel structure that is anchored into concrete foundations. The panel density for the AgriPV system is kept at fifty percent. A preliminary graphical representation of the PV structure design has been developed to illustrate the system's architectural implementation within this AgriPV project.

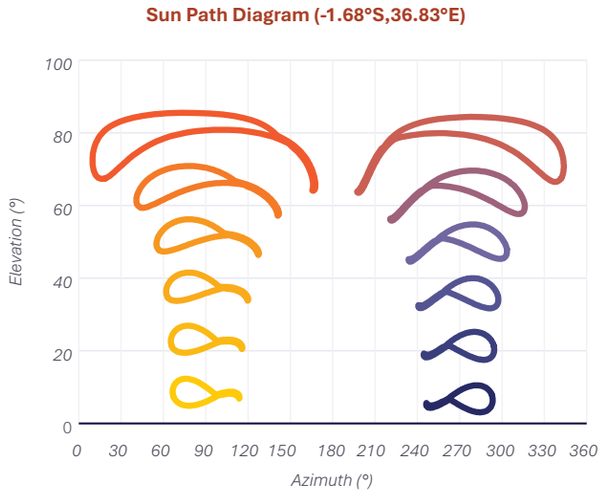
Figure 17: Specified PV structure design and system's architectural implementation within this AgriPV project.



For the project site, the sun path diagram has been plotted and presented in Figure 18. The optimum tilt angle is based on maximizing the total solar irradiation received on a tilted surface throughout the year. According to Global Solar Atlas, the optimum tilt for south facing fixed tilt PV array in Kenya is around 0^0. This means for maximum yield , the solar panels should be placed horizontally.

Considering the height difference the lowest point and highest point of the PV array depicted in the diagram above, and in conjunction with the sun path diagram, the minimum inter row spacing between the two PV arrays can be calculated.

Figure 18: Sun Path Diagram for the specified project Site



B. Comparative analysis of design aspects of AgriPV project with ground-mounted project

The performance of an AgriPV system can be assessed by examining its energy yield and Capacity Utilization Factor (CUF). This assessment enables a direct comparison between the AgriPV setup and a conventional ground-mounted solar system, highlighting the key differences between the two. To estimate the energy output of the hypothetical project, the team utilized photovoltaic power potential data from the Global Solar Atlas. The design of the hypothetical ground-mounted PV system adheres to standard industry practices, as outlined in the accompanying table.

Considering the previously mentioned parameters, the comparative analysis between AgriPV system and ground-mounted system is as follows:

Table 21: System comparison for Isinya Kenya

Parameter	For AgriPV (Array 1)	For conventional ground-mounted solar PV (estimated)	Remarks
COMMON DESIGN PARAMETERS			
PV panel	Polycrystalline Si PV	Polycrystalline Si PV	Some base parameters have been considered to be same for the AgriPV system as well as the ground-mounted system
Solar tracking	None, fixed tilt	None, fixed tilt	
Material of PV panel columns, rafters, and purlins	MS Steel	Hot dip Galvanized Mild Steel	
Project Area	800 m^2	800 m^2	
DIFFERENT DESIGN PARAMETERS			
Azimuth direction	North facing	North facing	
Tilt Angle	10 degrees	0 degrees	As per the Global Solar Atlas, the ideal tilt angle for solar panels in Kenya is 0 degrees. This is because Kenya lies very close to the equator, where sunlight strikes the surface almost directly throughout the year.
Ground clearance (lowest height of PV panel from ground)	3 m	0.6 m	AgriPV systems differ significantly from ground-mounted systems in terms of ground clearance primarily to accommodate agricultural activities beneath the solar panels.
DC System Capacity	62.1 kWp	80 kWp[45]	Design difference allows more modules to be installed in a conventional ground-mounted system.
Approx number of PV panels	180	232	
COMPARISON OF GENERATION			
Annual Generation per kWp	485.18 kWh	1538.9 kWh[21]	The energy output per unit capacity is quite low as compared to a ground-mounted PV system, mainly because the AgriPV setup is not operating at its full potential.
Capacity Utilization Factor (CUF on AC side)	5.5%	17.5%	
Annual Generation per m^2	37.66 kWh	153.8 kWh	The generation on unit land basis is significantly lower for AgriPV project.
Annual Energy Production	30130 kWh/year	123040 kWh/year	The overall energy generation from the conventional PV system is three times of that of the AgriPV system. **This is primarily because this system is not fully utilized currently.**

45 If horizontally mounted solar panels require less space per kilowatt-peak, a 1 kWp system would need approximately 10 square meters. Therefore, an 80 kWp installation could be accommodated within a total area of 800 square meters.

Therefore, if the land were solely dedicated to power generation, it is estimated that the energy output could be nearly three times higher compared to the current AgriPV setup.

C. Impact on Crop Cultivation in the AgriPV Project

In terms of Crop Cultivation, qualitative comparison of various yield parameters including yield, plant height, weight, diameter, leaf length and width etc., for the specified crops has been undertaken with the control plot of which the results are detailed in the table below.

Table 22: Impact of AgriPV project on crops

Cabbage	Smaller and lighter produce in AgriPV systems
Onion	Taller Plants but smaller and lighter bulbs in AgriPV systems
Coriander	Higher yield underneath the panels and taller Plants in AgriPV systems
Kale	Taller Plants, Heavier and wider leaves in AgriPV systems

D. Inferences

- **Project output -** The total consumption of Latina business solution is equal to 54.31 MWh/year. The AgriPV system generated 30.13 MWh/ year which is around 56% of the total energy consumed. If the system is fully utilized, it can supply up to 96.9 MWh/ year of energy and will overcompensate of the energy requirement. In that case, CUF of the AgriPV system would be around 17%, which is equal to that of a typical ground-mounted PV system.
- **Panel orientation-** If the tilt angle is 0 degrees, on the same land area, a typical ground-mounted solar system could produce approximately 1.2 times more energy than an AgriPV system operating at full capacity. The AgriPV system is tilted at an angle of 10 degrees to ensure effective water runoff, minimize dust accumulation and provide appropriate amount of sunlight to crops—benefits that a completely horizontal system would not be able to provide.
- **Crop characteristics and yield:** Smaller bulbs/ heads and lighter produce were noticed in cabbage and onions which can be attributed to inhibitions in fruit production due to presence of partial shade. Additionally, in the case of coriander, the taller plants with heavier and broader leaves indicate favourable microclimate conditions for cultivating leafy vegetables. This also suggests enhanced marketability, as crops like kale appeared greener and more vigorous.

The case study examines a 62.1 kWp AgriPV system at Latina Agribusiness Solutions (LAS) in Isinya, Kenya, a region characterized by a hot semi-arid climate. The system, designed with north-facing panels tilted at 10 degrees, aims to supplement LAS's electricity demand while enabling crop cultivation. A key finding is the significant difference in energy production between the current AgriPV setup and its potential output. Currently generating 30.13 MWh/year (56% of LAS's consumption), the system could produce up to 96.9 MWh/year if fully utilized, exceeding LAS's needs and achieving a capacity utilization factor comparable to conventional systems. The study highlights the trade-off between optimizing for energy generation and accommodating agricultural needs. A horizontal panel configuration, while maximizing energy output, would not provide the water runoff and partial shading benefits of the tilted design, which proved crucial for certain crops. While the AgriPV system reduced yields for some shade-intolerant crops, it notably increased yields and improved the quality of leafy vegetables (coriander, kale) and beans, likely due to reduced heat stress and optimized microclimate conditions. This underscores the importance of careful crop selection in AgriPV systems, particularly in semi-arid climates. The integrated rainwater harvesting system further enhances the system's value by providing supplemental irrigation. Overall, the LAS project demonstrates the potential of Agriphotovoltaics to enhance food security and energy access in challenging environments, while also highlighting the need for further research into optimizing system design and crop selection to maximize synergistic benefits.

GLOBAL AGRIPV PROJECT CASE STUDIES

2.2.5 Case Study IV - Sagar, Madhya Pradesh: Stakeholder consultation

Project overview

Team visited a grid-connected AgriPV project located in Sagar, Madhya Pradesh, with an installed AC capacity of 4 MW and a DC capacity of 4.5 MWp. The project was installed under the Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan (PM-KUSUM), Component A. Project overview details are tabulated in the following table:

Table 23 Project overview for Sagar AgriPV site

Aspect	Details
Project capacity	DC: 4.5 MWp, AC: 4 MW
Commissioning date	January 31, 2025
Land area	16 Acres (Family-owned, eliminating acquisition/leasing costs)
Project cost (Total)	INR 18.5 Crores (Including transmission line)
Financing structure	Debt-to-Equity Ratio: 70:30 (Debt from Central Bank of India)
Power purchaser	Madhya Pradesh Poorv Kshetra Vidyut Vitaran Company Limited (MPPKVVCL)
PPA term & tariff	25 Years at a fixed tariff of INR 3.07 per unit
Annual generation	Approximately eight million units (8 GWh)

Photovoltaic system design and technology

The PV system consists of 580 Wp solar modules from Jackson Solar, installed at a fixed tilt of 15 degrees with a south-facing azimuth and with ground clearance of 3.5 meters. A key design feature for agricultural integration is the elevated mounting structure. The PV system design and technology details are provided in the following table:



Table 24 Photovoltaic system design and technology for Sagar AgriPV site

Aspect	Details
Module technology	580 Wp solar modules from Jackson Solar; **bifacial, TopCON, and glass-to-glass technology.**
Module installation	Fixed tilt of 15 degrees with a south-facing azimuth for optimal solar irradiation capture.
Inverters	Fourteen string inverters, model WP-330KTL-H1, manufactured by Wattpower.
Structure materials	Cement poles with GI steel purlins and rafters.
Ground clearance	Significant **3.5 meters** clearance provided by the elevated design.
Row/Column spacing	**8-meter spacing between rows** and 5-meter spacing between columns to ensure sufficient sunlight penetration to crops.
Transmission line	Dedicated 4.2-kilometre, 11 kV single-circuit line (Cost: INR 1.05 Crores).
Power evacuation	Overhead DC and initial AC cabling to minimise losses and simplify maintenance.
Delivery point	5 MVA, 33/11 kV grid substation near Kishore Nyayalay, Kanera Deo.
Structural design	STAAD analysis was used to ensure the structure can withstand wind speeds up to 180 km/h.

Agricultural practices and crop performance

The crops are primarily cultivated across three growing seasons, i.e., Kharif (June-September), Rabi (October-February), and Zaid (March-May). All the crops are grown between the panels (8 m apart), whereas Papaya is cultivated under the panels. The details related to agricultural practices and crop performance are provided in the table below:

Table 25 Agricultural Practices and Crop Performance for Sagar AgriPV site

Aspect	Details
Soil type	Red soil with alternating patches of a mix of red and black soil.
Previous crops	Stevia and White Muesli.
Current crops	**Horticultural Crops:** Tomato, Brinjal, Sponge Gourd, Capsicum, Lettuce, Broccoli, Bottle Gourd, Strawberry, Dragon Fruit, Watermelon, Muskmelon, Papaya. **Field Crops (Experimental):** Maize (Sweet Corn), Wheat.
Cultivation strategy	Crops are grown across three seasons: Kharif (June-September), Rabi (October-February), and Zaid (March-May).
Shade utilization	Most crops are grown **between the panels** (8m apart); Papaya is cultivated directly **under the panels**.
Beneficial crops	**Tomato, Broccoli, Lettuce, Sponge Gourd, and Brinjal** exhibited excellent yield and fruit quality due to reduced heat stress. The shade facilitated an extended and off-season growing period, securing greater market returns.
Strawberry success	Promising yield and fruit quality due to the combined benefits of mulching and panel shading, which provided necessary cooling. A **dedicated shading net** connecting the two solar panels was installed to further mitigate heat stress and extend the growing period. An exclusive belt between panels is reserved for strawberries, precluding crop rotation.
Papaya success	Positioned directly beneath the panels, the design ensures plants receive light three times a day. This, combined with natural shade tolerance, resulted in excellent yield and fruit quality in hot/sunny conditions.



Table 25 (continued) Agricultural Practices and Crop Performance for Sagar AgriPV site

Aspect	Details
Dragon fruit	Cultivated between panels with an **overhead shade net structure** to limit direct sunlight and optimise growth by imparting inclined light.
Maize (Sweet Corn)	Satisfactory cob yield and three harvests, attributed to a significant **50% increase in spacing between plants** for proper light distribution. The crop is cultivated in raised beds to reduce waterlogging.
Wheat (Rabi season)	Panels are strategically placed in a **checkered pattern** for uniform light distribution. Yield improved from 70-80% in the first year to **100% in the second year**, with finer grain quality.
Water conservation	Wheat cultivation resulted in **25-30% water savings** due to reduced evapotranspiration and enhanced soil moisture retention.
Reduced yield crops	Capsicum, Bottle Gourd, and Muskmelon showed reduced yield when cultivated between the panels.

Water management and intercultural operations

Crop irrigation is supplied via drip irrigation, drawing from a 2.5 crore-litre rainwater harvesting system spanning two acres. This practice has significantly improved the land's water table. The details regarding water management and intercultural operations are provided in the table below:

Table 26 Water management and intercultural operations for Sagar AgriPV site

Aspect	Details
Irrigation method	Predominantly **drip irrigation**.
Water source	2.5 crore-litre **rainwater harvesting system** spanning two acres.
Water table impact	Rainwater harvesting has significantly improved the land's water table.
Water efficiency	The system reduced irrigation frequency from four times weekly to three. (25 to 30% water saving, about one irrigation cycle fewer per year)[46]
Mulching	Silver-coloured mulch is laid across all crops, enhancing soil moisture retention and reducing weed incidence.
Fertilization	Organic composting and vermicomposting are employed for efficient fertiliser supply.
Personnel comfort	The panel shade contributes to a more comfortable working environment for personnel performing intercultural operations.

46 Unlocking Solar at Scale: How Agriphotovoltaics Overcome Land Constraints in India's Energy Transition, TERI, 2026, https://teriin.org/sites/default/files/files/ETC_AgriPVStandalone.pdf

Project challenges and operational observations

Key project challenges and operational observations are given in the table below:

Table 27 Project Challenges and Operational Observations for Sagar AgriPV site

Aspect	Details
Financial/Commercial	Project cash flow and financial stability are significantly impacted by **persistent and substantial delays in receiving payments** from MPPKVVCL for supplied electricity.
Capital expenditure	Project capital expenditure is approximately **15% higher** than a similar capacity ground-mounted solar PV project; approximately 50% of this increase is on account of concrete pillars for the elevated structure.
Regulatory compliance	Post-commissioning requirement from the power utility is the mandated upgrade of the transmission line conductor from 'Rabbit' type to 'Raccoon' conductor. The owner is considering a 'Dog' type conductor at an additional unbudgeted cost of **INR 32 Lakhs** to meet Discom standards and reduce transmission losses.
Pests and disease	**Security lighting** inadvertently attracted a high prevalence of flies, causing damage to capsicum. The altered microclimate created by panel shade has contributed to a rise in specific pests and diseases detrimental to plant health.
Operations and maintenance	Daily O&M is managed by a single, dedicated technical staff member (from Khare Energy).
Module cleaning	Cleaning is performed **manually by local farm labourers** using a tractor fitted with pronged pipes and mops to reach the elevated surfaces.

2.3 Understanding from the Case Studies

Taken together, the case studies demonstrate that there is no single AgriPV configuration that can be replicated across all locations. Successful projects are those in which the agricultural system and the solar PV system are designed together, considering the local climate, crop characteristics, water availability, farming practices, landholding pattern, mechanisation requirements, grid conditions, and the interests of farmers. Variations in mounting height, inter-row spacing, module orientation, panel density, and shading levels directly influence both solar generation and agricultural performance. Wider spacing and elevated structures may reduce the amount of PV capacity that can be installed on a given area of land, but they can preserve access for cultivation, irrigation, machinery, and other farm operations. The overall performance of an AgriPV project should therefore be assessed on the combined value created from electricity generation, agricultural production, water management, and improved land use, rather than on solar output alone.

The case studies also show that crop response under AgriPV is highly context-specific. Moderate shading can reduce heat stress, soil-moisture loss, and crop exposure to extreme weather, particularly in hot and water-stressed regions. However, excessive or poorly distributed shading can reduce photosynthetically active radiation and negatively affect crop growth and yield. Crop selection must therefore consider shade tolerance, crop height, root characteristics, seasonal water requirements, growth cycle, market value, and compatibility with the proposed structure. In several cases, leafy vegetables, selected horticultural crops, legumes, fodder crops, and certain medicinal plants demonstrated greater compatibility with partial-shade conditions, while other crops required careful management of panel density and shading duration. This reinforces the need for crop-specific trials and monitoring before projects are scaled.

Another important lesson is that climate determines the primary purpose and design priorities of an AgriPV system. In arid and semi-arid regions, water conservation, reduced evapotranspiration, rainwater harvesting, dust management, and heat mitigation are particularly important. In tropical regions, drainage, ventilation, humidity management, corrosion protection, and resilience to heavy rainfall and high winds become more significant. In temperate and continental regions, seasonal solar availability, frost, snow loading, wind conditions, and the possibility of extending the growing season influence system design. The case studies therefore support a climate-responsive approach in which structural, electrical, agricultural, and operational decisions are adapted to local environmental conditions.

The experiences reviewed above have played an important role in shaping the framework developed in this report. They demonstrate that successful AgriPV deployment depends not only on technical performance, but also on clear land-use arrangements, farmer participation, access to finance, appropriate ownership and revenue-sharing models, reliable grid connectivity, institutional coordination, and long-term operations and maintenance. Lessons from these projects have therefore been used to identify the key technical, agricultural, financial, institutional, and operational parameters included in the framework across different climatic zone. They also highlight the importance of involving farmers from the planning stage, protecting agricultural activities throughout the project lifecycle, transparently allocating responsibilities and benefits, and continuously monitoring crop yield, soil moisture, irrigation demand, microclimate, energy generation, and maintenance requirements. Together, these practical insights provide the evidence base for a framework that can guide the planning, design, implementation, and long-term management of context-appropriate AgriPV projects.These collective findings provide the practical basis for the next chapter, which translates the lessons from real-world projects into a structured approach for AgriPV system design and configuration. Building on the observed relationships between climate, crops, shading, structural layout, agricultural operations, and energy performance, the next chapter examines how key parameters—such as system configuration, mounting height, inter-row and inter-panel spacing, module orientation, crop compatibility, irrigation, structural requirements, and electrical design—can be evaluated together. In this way, the report moves from understanding what has worked across different case studies to defining how context-appropriate AgriPV systems can be planned, designed, and adapted for deployment across diverse climatic and agricultural conditions.



CHAPTER 03

AgriPV Design Fundamentals



Chapter 1 established that AgriPV design needs to respond to the climatic, agricultural, and site-specific context in which a system is deployed. Building on this foundation, this chapter presents the core design principles and technical parameters that determine how solar PV systems can be integrated with agricultural production. Unlike conventional ground-mounted PV, AgriPV requires agricultural requirements to be considered alongside energy generation, structural integrity, accessibility, safety, and operational requirements from the outset. The chapter therefore introduces the key concepts, system configurations, crop compatibility considerations, and PV design parameters that provide the technical foundation for the climate-specific approaches developed in Chapter 4.

AgriPV system design and configuration form the technical and operational foundation for achieving symbiotic outcomes between solar energy generation and agricultural production across diverse climatic zones. This chapter defines the key design principles, configuration choices, and implementation pathways that enable dual land use to be both technically robust and agronomically viable. The focus is on establishing practical guidance that can be applied across different climatic zones, farming systems, and geographies, while remaining adaptable to local conditions.

3.1 Key concepts and terminologies

AgriPV design requires a common understanding of both agricultural and photovoltaic concepts because decisions on system configuration, spacing, mounting height, orientation, and shading are directly influenced by crop characteristics and farming practices. The following terminology provides the technical foundation for the design considerations discussed in the subsequent sections.

3.1.1 Agriculture related

Intercultural Operations:

Intercultural operations refer to the range of crop-management practices undertaken during the crop production cycle to support healthy growth and optimize yield. Depending on the crop and farming system, these activities may include:

- **Weeding:** Removing unwanted plants that compete with the crop for nutrients, water, and light.
- **Field preparation** refers to the series of agronomic practices carried out on the land before sowing or planting crops. This process typically involves clearing, plowing, tilling, leveling, and sometimes the application of fertilizers or soil amendments to create a suitable seedbed that promotes optimal seed germination and crop growth.
- **Hoeing:** Loosening the upper layer of soil to improve aeration, facilitate water infiltration, and control weeds.
- **Earthing up:** Pulling soil around the base of plants to provide physical support, prevent lodging, and improve root development.
- **Thinning:** Removing excess seedlings to maintain appropriate plant spacing and reduce competition among plants.
- **Gap filling:** Planting additional seeds or seedlings in areas where germination has failed or plant mortality has occurred, to maintain uniform plant population.
- **Mulching:** Covering the soil surface with organic or inorganic material to conserve soil moisture, reduce weed growth, moderate soil temperature, and reduce erosion.
- **Irrigation:** Supplying water to crops through appropriate methods (such as surface, sprinkler, or drip systems) to meet crop water requirements.
- **Plant protection measures:** Applying integrated pest and disease management practices, including biological, cultural, and chemical control measures, to protect crops from insects, pathogens, and other biotic stresses.

In an AgriPV context, these operations must be compatible with the physical layout of the solar structures, including access for machinery and manual labour beneath and between panel rows.

Morphological Features:

Morphological features refer to the external form and structure of plants. Understanding crop morphology is important in AgriPV to assess how plants will interact with shading patterns, rainfall distribution, and available space under solar structures. Key elements include.

- **Plant height and growth habit:** Whether the crop is low-growing, medium, or tall; erect, bushy, or vining, which influences suitability under different mounting heights and spacing of solar panels.
- **Leaf shape, size and arrangement:** Leaf area and orientation affect light interception and shade tolerance, which are critical for performance under partial shading.
- **Stem characteristics:** Stem strength, branching pattern, and flexibility determine how well crops withstand wind conditions around structures and potential mechanical contact with equipment.
- **Flower structure:** The arrangement of petals, sepals, stamens, and pistils.
- **Fruit type and seed characteristics:** Whether the fruit is fleshy or dry, and the size, shape, and texture of the seeds.

Photosynthetically Active Radiation (PAR):

Photosynthetically Active Radiation is the range of solar radiation wavelengths from 400 to 700 nanometers that plants use for photosynthesis. PAR determines the amount of usable light available to crops for biomass production and yield formation. In AgriPV systems, panel configuration, tilt, height, spacing, and transparency modify the quantity, timing, and distribution of PAR reaching the crop canopy. Managing PAR through design is central to achieving a balance between energy generation and agricultural productivity.

PAR can be measured in energy units (watts per square meter) or in quantum units (micromoles of photons per second per square meter), according to Black Dog LED. The amount of PAR available to a plant can vary depending on factors such as the time of day, altitude, and the presence of clouds or other light-blocking elements.

For AgriPV design, PAR availability is commonly evaluated using photosynthetic photon flux density (PPFD), expressed in µmol m^{-2} s^{-1}, and daily light integral (DLI), expressed in mol m^{-2} day^{-1}. These measures are more directly applicable to assessing the light environment experienced by crops than PAR as a wavelength range alone

Photosynthetic Productivity:

Photosynthetic productivity refers to the rate at which plants convert PAR into chemical energy stored in plant biomass through the process of photosynthesis. Productivity is often measured by assessing oxygen production or CO2 assimilation. It is a key driver of crop growth and yield. In AgriPV, photosynthetic productivity depends on:

- Light intensity and distribution over the day and season.
- Temperature and humidity conditions within the microclimate created by the panels.
- Soil moisture and nutrient supply.
- Crop-specific physiological traits and shade tolerance.

3.1.2 Technical related key concepts and terminologies

Capacity Utilization Factor (CUF)

The capacity utilization factor is a key performance indicator describing effectiveness of an installed PV system generates electricity relative to its rated capacity. Factors influencing CUF include solar radiation levels, panel orientation, shading, and seasonal variations, technology used, tracker etc (and could range anywhere between 18%-25%, depending upon system configuration and type of technology and tracker used and system age).

Land Equivalent Ratio (LER)

The land equivalent ratio is key performance indicator used for evaluating the efficiency of land use in AgriPV projects. LER compares the combined productivity of land used simultaneously for PV electricity generation and crop production against the productivity that would result from separate, single-use systems on equivalent land areas. An LER value greater than 1 indicates that the combined AgriPV system uses land more efficiently than standalone agriculture and standalone solar systems.

Ground Clearance

Ground clearance refers to the vertical distance between the lowest point of the PV module or supporting structure and the ground surface. Ground clearance affects:

- Possibility of using tractors, harvesters, and other machinery under the panels.
- Selection of crops based on their maximum height and growth pattern.
- Microclimatic conditions, including air circulation, temperature, and humidity beneath the modules.
- Exposure of electrical equipment and cabling to potential mechanical damage from animals or equipment.

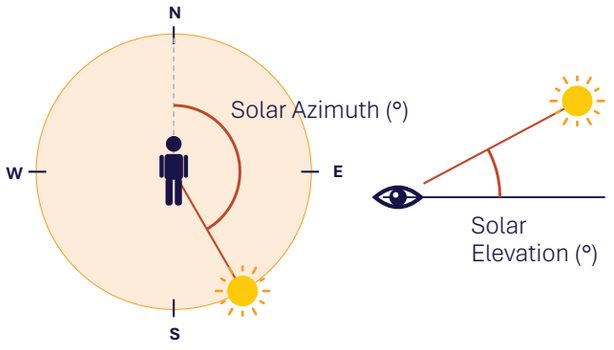
In AgriPV systems, panels are installed at greater heights to accommodate crop growth and farming activities, although higher clearance can lead to increased wind loads and structural requirements.

Next, the solar position at a given site and time determines both the direction of incident solar radiation and the resulting shadow pattern across the agricultural area. Two parameters are particularly relevant to AgriPV layout planning: solar elevation and solar azimuth, as illustrated in Figure 19.

Solar elevation angle

The solar elevation angle is the apparent height of the sun above the horizon, expressed in degrees. It changes throughout the day and across seasons as shown in Figure 19. The solar elevation angle influences the intensity and direction of sunlight incident on PV panels and ground. In AgriPV, this angle affects the length and movement of shadows, the distribution of light under the panels, and the resulting microclimate perceived by crops.

Figure 19: The representation for solar elevation angle and solar azimuth



Solar Azimuth

The solar azimuth angle describes the compass direction from which the sunlight is coming at a given location and time, typically measured in degrees from geographic north. It determines the horizontal direction of shadows cast by solar panels. Accurate understanding of solar azimuth is essential for orienting PV arrays and planning inter-row spacing so that shading patterns are compatible with crop requirements and field operations.

Sun Path Diagram

A sun path diagram is a graphical representation of the sun's trajectory across the sky at a specific location for different times of the day and months of the year. It combines solar elevation and azimuth information and is used to:

- Analyze seasonal shading and light availability beneath and between solar arrays.
- Determine optimal panel orientation and tilt angles.
- Assess potential shading on/from nearby infrastructure, trees, or fields.

In AgriPV design, sun path diagrams are a foundational tool for visualizing and optimizing the interaction between solar structures and agricultural layouts. There are several open-source online tools that can be used for plotting sun path diagram such as World Solar Atlas, and PVGIS[47].

Azimuth of Solar PV Project

The azimuth of a solar PV project refers to the orientation of the PV modules relative to true north, expressed in degrees. For example, in the Northern Hemisphere, south-facing arrays (azimuth around 180°) are typically adopted to maximize annual energy yield. In AgriPV, alternative orientations such as east–west can be used to improve the temporal distribution of light and reduce midday shading intensity on crops. The chosen azimuth has direct implications for both energy generation profiles and crop light regimes.

47 Details provided in Table 34: Minimum Data Requirements for Site Suitability Assessment for AgriPV installation and configuration

Optimal Tilt Angle of Solar PV Array

The tilt angle is the angle between the plane of the PV module and the horizontal ground surface. The optimal tilt angle is the angle at which the array captures the maximum useful solar radiation over the target period, usually on an annual basis.

In AgriPV, the optimal tilt must be considered:

- Annual energy yield.
- Desired shading patterns and PAR availability for crops.
- Rainwater runoff and potential for rainwater harvesting.
- Snow shedding in cold climates and wind loading in exposed sites.

Fixed and tracking systems adopt different strategies for tilt optimization, often requiring detailed modelling to balance power output with agricultural outcomes.

Inter-row spacing

Inter-row spacing refers to the distance between rows of solar panels. This spacing must be calculated carefully to avoid shading between panels, which can significantly reduce energy yield. In AgriPV systems, inter-row spacing is often increased to accommodate crop growth and agricultural activities, balancing energy production with farming needs.

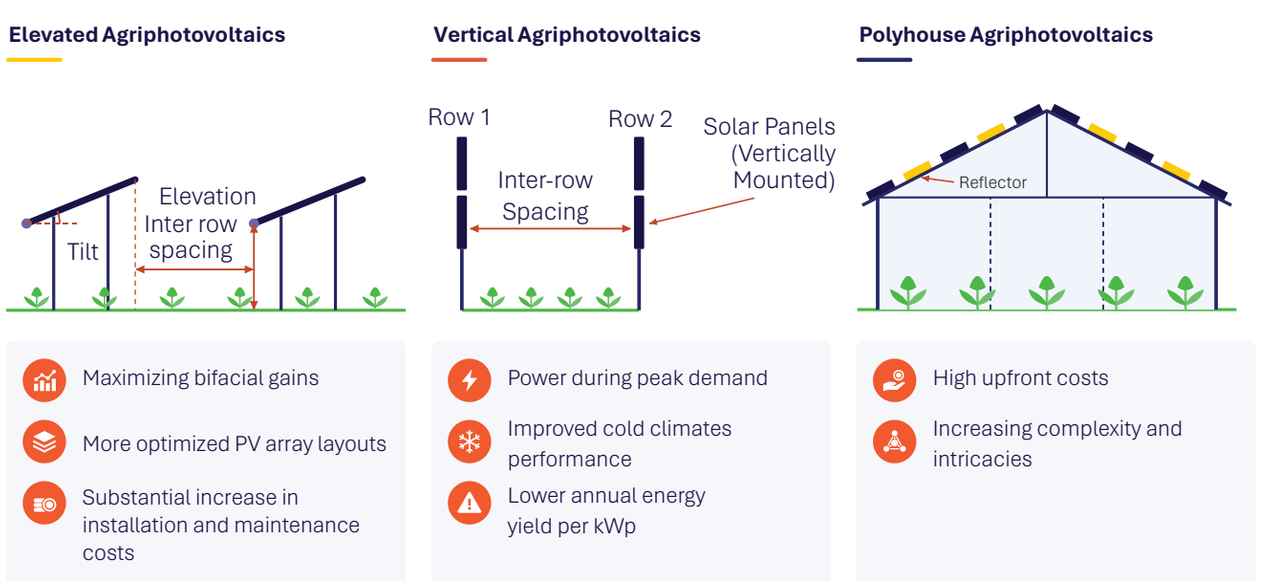
2.2 Layout Types: Elevated / Vertical / Polyhouse

The choice of AgriPV configuration determines how agricultural activities interact spatially and operationally with the solar installation. It influences light distribution, microclimate, machinery access, structural requirements, water management, and PV energy yield. Three configurations are examined in this framework: elevated AgriPV, vertical AgriPV, and polyhouse AgriPV. These configurations represent different approaches to balancing agricultural production and solar generation and should be selected according to crop characteristics, farming practices, climatic conditions, and project objectives. The different AgriPV layouts are illustrated below:

Elevated AgriPV

Elevated AgriPV systems are characterized by PV panels mounted on tall structures, typically 2.5 to 4 meters[48] for the easy movement of farming machineries, but is also dependent on the local wind and soil condition and the structural strength as shown in Figure 20. This configuration creates a continuous overhead canopy that permits full-scale agricultural operations directly

Figure 20: Illustration for elevated AgriPV



48 https://www.iasgyan.in/daily-current-affairs/agri-photovoltaics-agripv-challenges-benefits-and-way-forward

beneath the panels. The layout is suitable for a wide range of crops as per their specific conditions under which they fit, including tall varieties such as maize, mustard, and some fruit trees, and allows continued use of conventional agricultural machinery without major modification.[49]

The overhead canopy moderates microclimatic extremes by reducing direct solar radiation, lowering soil and canopy temperatures, and decreasing evapotranspiration rates. This leads to significant water savings, particularly in arid and semi-arid regions, and can help prevent heat stress in sensitive crops. The structure also provides physical protection against hail, strong winds, and heavy rainfall, thereby reducing crop damage risk and enhancing farm resilience. In elevated AgriPV systems, the underlying surface influences the performance of bifacial PV modules by affecting the amount of solar radiation reflected onto the rear side of the panels. Surfaces with higher albedo, such as light-colored soil or certain light-colored vegetation, can enhance rear-side irradiance and increase bifacial energy yield. Conversely, dense crop canopies, darker vegetation, or low-reflectivity soils may reduce ground reflectivity and lower rear-side irradiance. Therefore, the magnitude of bifacial gain depends on site-specific factors including soil characteristics, crop type, vegetation density, and climatic conditions. In addition, module density and array spacing should be carefully optimized, as tightly packed canopies can limit the amount of sunlight reaching the ground, reducing reflected radiation and the associated albedo-driven bifacial gain.

However, the tall, robust support structures required to withstand considerable wind loads (especially in tropical regions) and snow loads (in temperate/continental regions) lead to a substantial increase in material and installation costs, often making these systems more expensive per kilowatt-peak (kWp) than conventional solar PV projects. Furthermore, accessing panels for cleaning and maintenance becomes more challenging, potentially necessitating specialized lifts or robotic cleaning solutions. The different aspect of elevated system are discussed below in Table 28.

Table 28: Key aspects for elevated AgriPV layout

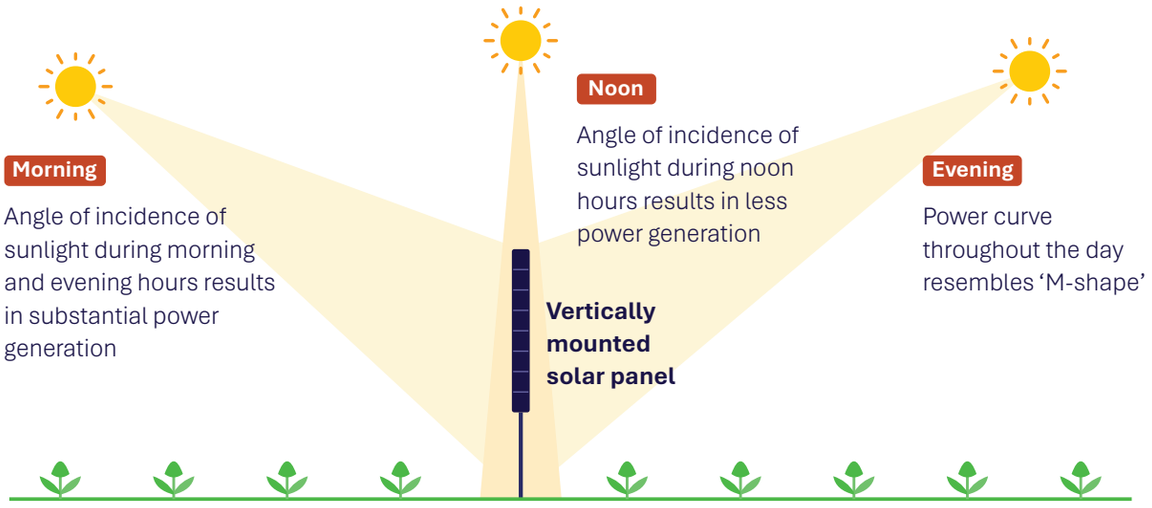
Aspect	Description & details
System profile	Solar panels are mounted high above the ground on a robust structure, creating a protective canopy. Farming occurs directly **under** the panels.
Key advantages	• **Creates a Protective Microclimate:** Shields crop from extreme heat, frost, and hail. • **Superior Water Conservation:** Can reduce soil evaporation and crop water demand • **Supports Selected High-value Crops:** Makes it possible to grow sensitive crops (leafy greens, berries) in harsh climates. Can support selected high-value crops • **Uniform Land Use:** Allows for consistent cultivation across the entire plot.
Key trade-offs	• **High Initial Cost:** Significantly more expensive to build due to the need for more steel and stronger foundations. • **Complex Maintenance:** Panel cleaning and repairs are difficult and costly at height. • **Risk of Over-Shading:** Poor design can block too much light, requiring careful optimization of panel density. • **Machinery Constraints:** May require specialized, lower-profile farm equipment depending on the system height.
Best suited for	Projects prioritizing **water conservation** and **crop quality** in harsh climates (especially arid zones), and for cultivating **high-value, sensitive crops** where the improved yield justifies the higher investment.

3.1.3 Vertical configuration

Vertical AgriPV systems typically use bifacial modules installed in near-vertical rows as shown in Figure 21. Row orientation, commonly north–south or east–west depending on the project objective and latitude, influences the timing and distribution of solar generation and shading across the agricultural area.”. This configuration optimizes sunlight capture by solar panels during morning and evening hours as illustrated below.

49 Elevated AgriPV systems can physically accommodate a wide range of crop heights where module elevation, structural spacing, and machinery clearances are appropriately designed. However, physical clearance does not by itself establish agronomic suitability. Light-demanding crops such as maize should be considered only in low-shade, widely spaced, or otherwise crop-optimized layouts in which seasonal crop-level radiation and harvesting access are demonstrated to be adequate. Crop suitability should be confirmed through site-specific light modelling and local agronomic evidence.

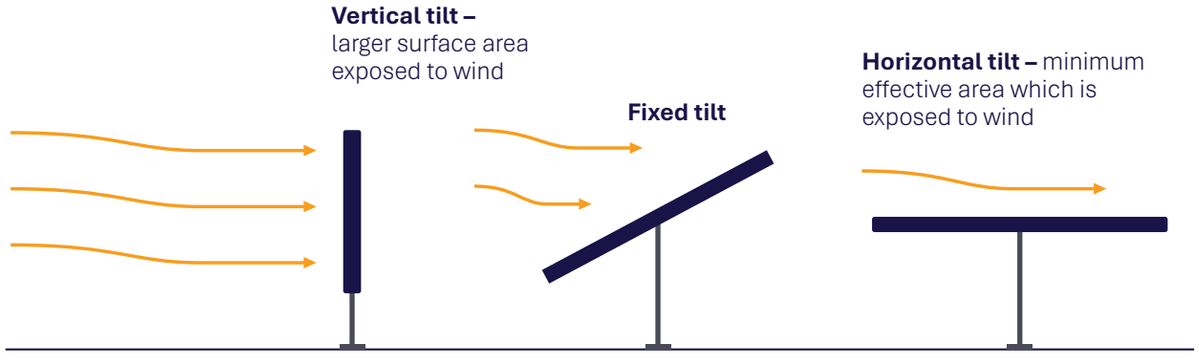
Figure 21: Illustration of incident sunlight for vertical AgriPV throughout the day



The vertical layout is well-suited for crops that benefit from morning or evening insolation and can tolerate some midday shading. It also facilitates the creation of distinct microclimates on either side of the panel array, accommodating different crop types.

The vertical panels can also function as a windbreak, protecting crops from wind damage and reducing soil erosion as shown in Figure 22. The vertical layout of panel leads to extensive pressure on panels during high wind speeds such as during dust storms. The extensive pressure necessitates installation of stronger structural columns in vertical AgriPV layout as compared to elevated AgriPV layout.

Figure 22: Illustration to show increased wind load for vertical AgriPV



Wind load decreases with tilt as the angle reduces the effective area exposed to wind pressure.

A critical consideration is that crops directly adjacent to the panels will experience strong morning/evening sun followed by midday shade, necessitating careful selection of crops that can tolerate or even thrive under such dynamic light conditions. Additionally, crops at the very edges of the vertical arrays might experience different environmental conditions compared to those situated further within the field.

East-west oriented vertical bifacial panels can generate substantial power during morning and evening peak demand periods, aligning effectively with typical residential and commercial load profiles. Vertical panels are less susceptible to snow accumulation compared to tilted panels as their upright position makes it harder for snow to accumulate. This leads to improved winter performance in snowy regions. However, vertical panels

do not consistently receive optimal perpendicular sunlight throughout the day, which may result in a lower annual energy yield per kWp, depending on the location's latitude.

Vertical AgriPV is particularly relevant where maintaining full ground accessibility is important, for example in mechanized farms, pasture-based livestock systems, or landscapes where minimal alteration of land surface infrastructure is required. It is also suited to regions with strong winds, where the windbreak function delivers additional agronomic benefits, and to settings where the distinctive generation profile holds value for local grids or mini grids. The key aspects for vertical AgriPV layout are summarized in the Table 29 below:

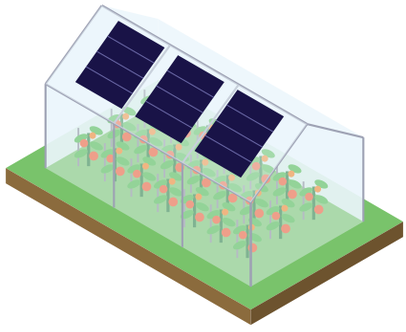
Table 29: Key aspects for vertical AgriPV layout

Aspect	Description & details
System profile	Bifacial (two-sided) panels are installed vertically in rows, typically oriented North-South or East-West. Farming occurs with near-total freedom **between** the rows.
Key advantages	• **Maximum Land & Machinery Access:** Allows use of large, conventional farm equipment with minimal obstruction. • Distinctive Time-Varying Shading: Produces relatively limited shading during some periods but stronger morning and afternoon shading, depending on row orientation and solar position that preserves the most productive hours of sunlight for sun-loving crops. • **Grid-Friendly Power:** Produces energy peaks in the morning and afternoon, matching electricity demand. • **Easy maintenance:** Due to the vertical nature of the PV module, it requires minimal cleaning. • **Acts as a Windbreak:** Reduces soil erosion and protects crops from wind damage.
Key trade-offs	• **Higher Land Requirement:** Needs more land area to achieve the same energy capacity as a conventional solar farm. • **Higher Technology & Foundation Cost:** Requires more expensive bifacial panels and robust foundations to handle wind loads. • **Directional Shading:** Creates significant shadows in the early morning and late afternoon that must be managed. • **Lower Energy Yield Per Panel:** Captures less total energy per day compared to an optimally tilted panel.
Best suited for	Modernizing large-scale, mechanized farming operations; projects where **grid stability** and **peak power pricing** are key economic drivers; and regions where maximizing agricultural access is a higher priority than maximizing energy density.

3.1.4 Polyhouse AgriPV

Polyhouse AgriPV combines protected cultivation with integrated solar PV systems. In this layout, crops are grown within controlled-environment structures (such as greenhouses or polyhouses), and PV modules are mounted on or integrated into the polyhouse roof or superstructure. The PV modules partially replace conventional cladding materials, such as plastic film or glass, and can be either opaque, semi-transparent, or configured as spaced rows to admit controlled levels of natural light. The illustration for polyhouse AgriPV is shown in Figure 23.

Figure 23: Illustration for polyhouse AgriPV



The defining feature of polyhouse AgriPV is the deliberate use of microclimatic modifications created by both the enclosure and the PV modules to optimize crop cultivation. The polyhouse envelope allows regulation of temperature, humidity, and airflow, while the PV modules modulate incident solar radiation and can be combined with additional features such as reflectors, diffusers, shading nets, ventilation systems, and automated irrigation.

The cost of polyhouse construction and integrated PV is significantly higher than traditional open-field farming. The construction of polyhouse itself is expensive, requiring durable materials and climate control systems to withstand harsh weather. Adding solar panels further raises costs, as it involves specialized electrical infrastructure and careful design to avoid interfering with plant growth. It also necessitates specialized knowledge in both horticulture and solar energy management to optimize conditions for both energy generation and agricultural production. The design must integrate structural, electrical, and horticultural requirements, thereby increasing its complexity. The specialized PV integration, coupled with the polyhouse infrastructure, typically results in a higher upfront cost. Furthermore, access for cleaning and maintenance within a polyhouse can be more intricate due to the enclosed nature of the structure. The key aspects are described in the Table 30 below.

Polyhouse AgriPV is particularly suited for high-value horticultural crops, including vegetables, berries, flowers, and nursery plants, where precise environmental control and high product quality are essential, and where year-round or extended-season production is economically attractive.

Table 30 Key aspects for polyhouse AgriPV layout

Aspect	Description & details
System profile	A fully integrated greenhouse where semi-transparent solar panels form the roof, creating a high-control agricultural environment powered by its own structure.
Key advantages	• **Enhanced Environmental Control:** Precise management of temperature, water, and pests. • **Year-Round Production:** Enables multiple harvests per year, independent of external weather. • **Potential for Improved Resource Efficiency:** Exceptionally low water and pesticide use. • **On-Site Power Generation:** Panels power the greenhouse's own fans, pumps, and lights, reducing operational costs.
Key trade-offs	• **Highest Initial Cost:** Extremely high investment required for the specialized structure and panels. • **Complex Heat Management:** Prone to overheating, requiring sophisticated cooling and ventilation systems. • **Reduced Sunlight:** Limits the types of crops that can be grown without supplemental lighting. • **High Operational Expertise:** Requires advanced skills in horticulture and climate control systems.
Best suited for	Specialized producers of **high-value, premium crops** where **year-round supply, quality control, and resource efficiency** are the primary goals, and the high initial investment can be justified by high market prices.

The design of an AgriPV system requires systematic coordination between agricultural requirements and photovoltaic engineering parameters. Unlike conventional solar projects, AgriPV projects must be configured so that agricultural needs define the main design levers, while energy generation, cost, constructability, and operational safety are optimized within those constraints.

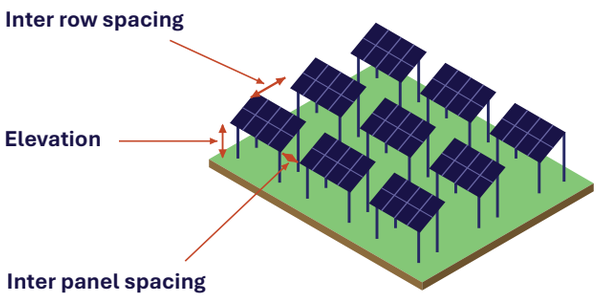
The three configurations described above demonstrate that system architecture alone does not determine AgriPV suitability. The effectiveness of a configuration depends on how its physical and electrical characteristics interact with crop requirements, shade tolerance, farming practices, water availability, and site conditions. The next section therefore shifts from configuration-level considerations to the agricultural parameters that should drive detailed AgriPV design.

3.2 Shade Tolerance & Crop Compatibility

3.2.1 AgriPV System Design Matrix: Key Parameters and Influencing Factors

Six key design parameters directly influence the performance and agricultural compatibility of AgriPV installations (as shown in Figure 24): Inter-Row Spacing, Mounting Height, Tilt Angle, Inter-panel Spacing, Panel Type, and Soil Characteristics. These parameters must be systematically evaluated across five critical agricultural considerations: Crop Height and Physical Structure, Climatic Zone, Shade Tolerance, Crop Water Requirements, and Compatibility with Farm Machinery.

Figure 24: Illustration for mounting height, inter row spacing, and inter panel spacing in Agriphotovoltaics system



AgriPV Key Design Parameter Frameworks:[50]

Table 31 details the critical design parameters, or 'levers,' that are adjusted to create an optimized AgriPV system. It systematically illustrates how key design parameters for solar panel installation are influenced by a range of agricultural, environmental, and operational factors. The rows of the matrix represent the main design choices you need to make for the solar array (e.g., panel height, spacing), while the columns represent the influencing factors you must consider (e.g., crop type, climate, farm machinery). Each cell in the matrix provides a specific recommendation or consideration, helping to optimize the design for both crop growth and energy production.

It should be noted that inter-row spacing, mounting height, module dimensions, and module transparency jointly affect crop-level radiation, temperature, humidity, wind, rainfall redistribution, soil evaporation, crop transpiration, and field access. Their effects should not be interpreted independently. Selection of these parameters should be based on the crop's seasonal light requirement, acceptable agricultural-performance threshold, water regime, farm operations, local climate, and PV-energy objectives. Opaque, semi-transparent, or spaced-module arrangements should therefore be selected through combined energy, light, microclimate, and agronomic assessment rather than crop water requirement alone.

50 Source: PwC analysis and stakeholder consultation



Table 31: Key design parameters for an AgriPV system

Design Parameter	Crop Height & physical traits	Climatic Zone	Shade tolerance	Crop Water Requirement	Compatibility with Farm Machinery	Soil Characteristics
Inter-Row Spacing: *Governs light availability for crops and provides access for machinery.*	Taller crops (~ 3 m) require wider inter-row spacing for minimal shading	Wider spacing in high latitude/arid zones, narrower in humid/temperate zones	Reduced spacing for shade-loving crops; Increased spacing for shade-sensitive	Wider spacing can help retain soil moisture and improve water use e iciency (WUE)[51]	≥6 m spacing for combine headers and tractor turnarounds; ≥5 m for small tractors or hand tools	Wider spacing for poorly drained soils to allow runoff paths; Tighter where soils drain well
Mounting Height: *Provides physical clearance for crops and machinery; influences the microclimate (airflow, shade).*	Optimized based on maximum mature height of crop ensuring space for growth and machinery	Higher in hot zones to improve airflow; lower in colder climates wind protection.	Shade-tolerant crops prefer lower mounts for consistent shade: shade-intolerant need higher mounts for uniform light.	Higher mounts can reduce evaporation and create a cooler microclimate[52]	≥2.5 m to pass tractors, sprayers, harvesters; Adjustable tilt mounts for narrow machinery	Soil fertility and water retention influences microclimate-requiring higher mounts for airflow or lower mounts for thermal benefits.
Tilt Angle: *Balances maximizing solar energy capture with providing optimal light distribution to crops.*	For tall crops, tilt angle optimization considers both solar gain and enables light distribution	Optimized for solar gain considering seasonal sun paths and potential snow loads in colder regions.	Steeper tilt increases light gaps for sun-loving crops; lower tilt provides more uniform shade	Optimized to control shade patterns, based on location of rainfall	Steeper tilt angle for large scale machinery with wider rows, Lesser tilt for small machinery in closer rows	
Inter-panel spacing: *Fine-tunes the amount of sunlight that "drips" through the array to the crops and soil directly below.*	Taller or light-intensive crops prefer wider spacing to allow more sunlight	Wider in sunny, arid zones to reduce shade; can be tighter in less sunny or humid zones.	Increasing panel gaps improves light diffusion for shade-intolerant crops.	Adjusting affects the amount of direct rainfall, thereby soil moisture	Adjusted to allow for smaller specialized machinery access within arrays	Affects light and rainfall distribution to the soil, which is crucial for managing soil moisture
Panel type: *Determines the foundation design and informs the overall land management and agricultural plan.*	Choice of panel based on crop's light requirements relative to its height	Bifacial panels are highly suitable in high-albedo areas	Semitrans-parent panels suit shade-tol-erant crops; vertical bifa-cial panels maximize inter-row light	Opaque panels for high water requirements, semitranspar-ent panels for moderate water requirements		

51 Wider spacing generally increases crop-level radiation and may also increase evaporative exposure; its net effect on soil moisture and water-use efficiency depends on crop cover, rainfall redistribution, irrigation, wind, and seasonal conditions

52 Mounting height influences shade intensity, shade distribution, and ventilation. Higher mounts generally diffuse the shade footprint and can increase air exchange; the resulting effect on crop temperature and evapotranspiration is site- and configuration-specific.

Advanced Design Enhancements

To further boost agricultural synergy, integrated features can be added to the core design. Reflectors can be mounted to redirect sunlight into shaded zones, improving light uniformity and supporting crop growth. Additionally, rainwater harvesting systems with gutters can capture panel runoff for irrigation solutions that simultaneously conserve water in arid regions and prevent soil erosion. Reduced soil evaporation, reduced crop transpiration, lower crop evapotranspiration, reduced irrigation application, improved water-use efficiency, and improved irrigation-water productivity are related but distinct outcomes. A reduction in evapotranspiration should not automatically be reported as irrigation-water saving or improved water productivity. Water-saving claims should be based on measured irrigation volumes or a validated crop-water balance, while water productivity should relate marketable crop output to the relevant quantity of water used. By understanding these fundamental design principles and their associated trade-offs, stakeholders can make informed decisions that balance energy goals with agricultural productivity from the very beginning of the project planning process.

3.2.2 How shade tolerance of crops determines AgriPV Feasibility

Understanding the shade tolerance of agricultural crops across these zones is crucial for assessing AgriPV feasibility. Shade Tolerance[53] is technically defined by a crop's ability to grow and produce under reduced Photosynthetically Active Radiation (PAR), often measured by yield response to shading levels (e.g., 20-50% reduction in solar radiation, RSR). Crop response to AgriPV shading should be interpreted from the direction and magnitude of yield or quality change across an explicitly stated range of reduction in solar radiation. For preliminary screening, crops may be described as:[54]

- **Shade-Benefiting:** Marketable yield or quality is maintained or improved within the evaluated RSR range because reductions in heat or water stress outweigh the effect of reduced radiation.
- **Relatively Shade-Tolerant:** Marketable yield remains within the project-defined agricultural-performance threshold across the evaluated RSR range, although some decline may occur.
- **Shade-Susceptible:** Marketable yield or quality declines beyond the acceptable project threshold within the evaluated RSR range.

Crop shade response is one component of AgriPV feasibility and should be evaluated together with configuration, seasonal light distribution, water regime, mechanization, crop value, and farming-system requirements.In tropical (A) climates, shade-tolerant perennials like coffee, cocoa, bananas, cassava, and spices (black pepper, ginger) are ideal, as AgriPV systems can provide beneficial shade, reducing water loss and heat stress. Dry (B) climates can also benefit from shade for water conservation, making shade-tolerant crops like forages, root crops (sweet potatoes), and some leafy vegetables attractive options for cultivation under AgriPV systems. However, shade-susceptible crops like maize and cotton are less feasible in these regions due to potential yield losses. Temperate (C) climates offer a wider range of suitable crops, including berries, leafy vegetables, root crops, and forages, due to their inherent shade tolerance. AgriPV is highly feasible in these zones, particularly in Mediterranean and humid subtropical areas, provided careful panel design optimizes light distribution. Continental (D) climates allow for cultivation of shade-tolerant cereals like wheat and barley, along with forages and some vegetables, but the short growing season and cold winters may limit options, making AgriPV more suitable in warmer subtypes. The table in Annexure D provides a detailed feasibility assessment for integrating a wide range of crops within AgriPV systems. For each major crop type, it systematically presents a scientific evaluation of its inherent shade tolerance, referencing key metrics like acceptable Relative Solar Radiation (RSR) reduction and potential yield impacts the detailed table in Annexure C.1 provides a detailed feasibility assessment for using different crops in AgriPV systems. It links each crop type to its scientific shade tolerance and then gives a practical recommendation on how well that crop might grow under solar panels, helping to identify the most suitable plants for dual-use land management.

53 This classification of shade tolerance for crops is derived from studies like the meta-analysis by Beck et al. (2022), which developed crop type-specific yield response curves, estimating relative yields compared to unshaded controls ([Contrasting yield responses at varying levels of shade suggest different suitability of crops for dual land-use systems: a meta-analysis] (https://link.springer.com/article/10.1007/s13593-022-00783-7)).

54 These categories are indicative rather than fixed physiological classifications. Reported responses should be interpreted with reference to crop species and cultivar, growth stage, duration and timing of shade, climatic conditions, water and nutrient status, and AgriPV configuration. Thresholds derived from one site or shading method should not be treated as universally applicable.



3.2.3 How Regional Farming practices shapes AgriPV Design

The following table[55] provides a broad overview of dominant agricultural practices within different climatic zones. Its objective is to connect these climate-driven farming realities to the core opportunities and design considerations for AgriPV systems. By understanding the primary challenges and goals of agriculture in a given region, whether it's conserving water, managing heat, or maximizing sunlight—we can better tailor solar array designs to create a truly synergistic dual-use system.

55 ***Disclaimer:*** The information presented in this table is a high-level summary intended for general guidance and educational purposes. The feasibility and success of an AgriPV project are critically dependent on site-specific factors, including local microclimate, soil type, crop variety, and specific market economics. The design implications provided are generalizations and do not replace the need for detailed, on-site agronomical and engineering analysis before any implementation.

Table 32: Overview of dominant agricultural practices within different climatic zones

Climatic Zone	Category	Description	Relevance for AgriPV Design
Hot Arid	**Practices**	• Cultivation is almost entirely dependent on irrigation, often using water-saving methods like drip systems. • Focus on heat-tolerant and drought-resistant crops (e.g., date palms, sorghum, millet).	**Primary Goal:** Reduce water use and heat stress. **Design Focus:** Maximizing shade from panels to lower soil and crop temperature, reduce evaporation, and improve water efficiency. Rainwater harvesting systems on panels have become highly valuable. Panel density can be higher to protect crops.
	Challenges	• **Extreme Water Scarcity:** Exceptionally low and unreliable rainfall makes non-irrigated farming impossible. • **Soil Salinization:** High evaporation rates leave salt deposits in the soil, reducing fertility. • **Intense Heat & Sun:** Scorching temperatures and direct sun stress crops and increase water loss.	
Semi-Arid	**Practices**	• High-risk rain-fed farming of drought-resistant staples (e.g., millet, chickpeas) • Widespread agro-pastoralism, where livestock grazing is integrated with cropping as a risk-management strategy.	**Primary Goal:** Conserve soil moisture and provide stable conditions. **Design Focus:** Spacing panels to create a microclimate that reduces evapotranspiration. Provides shade for livestock. Panel layout must consider potential for water harvesting and manage runoff to prevent soil erosion during intense downpours.
	Challenges	• **Erratic Rainfall:** Precipitation is low, unreliable, and highly seasonal, making crop failure a constant risk. • **Desertification:** The fragile ecosystem is vulnerable to soil erosion from wind and water, leading to irreversible land degradation.	
Tropical	**Practices**	• Year-round cultivation with high-density, multi-story cropping (agroforestry) that mimics forest layers. • Production of key global commodities like coffee, cocoa, bananas, and palm oil, often in shaded conditions.	**Primary Goal:** Manage light and water to control undergrowth and disease. **Design Focus:** Using semi-transparent or spaced-out panels to allow sufficient, diffused light for shade-loving crops. Elevated structures are needed for multi-story cropping. Panel layout must manage intense rainfall to prevent soil erosion.
	Challenges	• **Poor Soil Quality:** Constant, heavy rainfall leaches nutrients from the soil, making it acidic and infertile. • **High Pest, Disease & Weed Pressure:** The warm, humid conditions are perfect breeding ground, requiring constant management.	
Temperate	**Practices**	• Highly productive, four-season agriculture dominated by large-scale, mechanized farming • Diverse cultivation of staple grains (wheat, corn), high-value fruits, and vegetables.	**Primary Goal:** Balance sunlight for crops with energy production. **Design Focus:** Optimizing panel spacing and orientation (e.g., vertical bifacial) to ensure high-value crops receive enough sunlight during the limited growing season. Design must accommodate large farm machinery and manage water to prevent soil erosion and nutrient runoff.
	Challenges	• **Defined Growing Season:** Cultivation is limited by the frost-free period. • **Soil Degradation:** Intensive mechanization and monoculture can lead to soil compaction, erosion, and nutrient runoff into watersheds.	



Table 32: (continued) Overview of dominant agricultural practices within different climatic zones

Climatic Zone	Category	Description	Relevance for AgriPV Design
Continental	**Practices**	• Large-scale, highly mechanized monoculture of hardy grains (wheat, corn, soy) in global "breadbasket" regions. • Farming activities are compressed into a very short, intense summer growing season.	**Primary Goal:** Maximize light availability during the short season. **Design Focus:** Low-density panel arrays with wide spacing to minimize shading is critical. Dynamic systems (trackers) or vertical east-west panels can help maximize sunlight on crops during peak growing hours. Structural design must withstand heavy snow loads in winter.
	Challenges	• **Extreme Temperature Swings:** A vast difference between hot summers and severely cold winters. • **Short Growing Season:** A narrow window between frosts dictates what can be grown and creates high pressure for timely operations.	



3.3 PV System Design, Sizing and Integration

3.3.1 Climate-responsive layout selection

This section discusses a strategic approach to solar panel layout, emphasizing its role in microclimatic modulation across diverse climatic zones and its subsequent impact on the suitability of various crop types.

Microclimate Effects of Solar Panel Layout Across Climatic Zones

Selecting the appropriate layout depends on the specific microclimatic needs of the crops. Different configurations can influence factors such as temperature, humidity, and light distribution. Below are a few examples illustrating how solar panel layouts impact microclimates across various climate types.

- In **Dry (Arid) Zones**, where extreme heat and water scarcity prevail, solar panels provide critical shade, mitigating soil temperature and reducing evapotranspiration. This fosters a cooler, more humid microenvironment, promoting water conservation and safeguarding crops from heat stress.
- In **Dry (Semi-Arid) Regions**, panels help to moderate temperature fluctuations and reduce wind speeds, which in turn improves soil moisture retention and minimizes erosion.
- In **Tropical Climates**, characterized by intense solar irradiation and intense rainfall, solar panels shield crops from excessive solar radiation and heavy precipitation, preventing leaf scorching and soil erosion while providing a slight cooling effect.
- In **Temperate Zones**, solar panels can extend the growing season by buffering against early frosts and excessive summer heat. They also contribute to stable humidity and soil moisture levels, supporting consistent crop development.
- In **Continental Climates**, marked by extreme seasonal variations, solar panels act as climate buffers, mitigating the impacts of both summer heat and winter cold. This creates a more stable microclimate that protects crops from temperature extremes and wind damage.

The localized microclimate established by solar panels in an AgriPV system is pivotal in determining crop suitability and productivity. By moderating temperature, increasing humidity, reducing wind speed, and enhancing soil moisture retention, this optimized environment can significantly reduce plant stress, boost photosynthetic efficiency, and extend growing seasons.



3.3.2 Structural and geometric design parameters

Designing AgriPV systems entails complete analysis of many design factors, which are co-dependent, such as panel orientation, tilt angle, ground clearance, inter-row spacing and tracking systems. These design elements are discussed in detail in this section as follows:

Panel Orientation: Panels should be positioned and oriented in such a way that solar exposure is maximized for energy generation while also ensuring potential benefits to the most suitable crop.

For fixed-tilt systems, panels are typically oriented towards the equator (south in the Northern Hemisphere, north in the Southern Hemisphere) to maximize annual solar energy capture. However, in AgriPV, alternative orientations, such as east-west facing arrays, may be employed to distribute light more evenly throughout the day, mitigating periods of intense shading directly beneath the panels. Additionally, reflective surfaces and the use of reflective coatings on the back of bifacial panels can be strategically implemented to further enhance energy capture without inducing excessive shade on the crops.

Array tilt angle: The optimal tilt angle for array is necessary on account of seasonal sun path variations to maximize energy yield. For AgriPV system, a steeper tilt angle can increase the inter-row spacing required but allows for greater light penetration between rows, benefiting susceptible crops. Conversely, a shallower tilt might reduce inter-row shading but could concentrate shade directly beneath the panels.

The selection of tilt angles is thus a compromise between maximizing energy yield and ensuring adequate PAR for the underlying crops. Consideration must also be given to snow shedding in continental climates to prevent excessive loading and prolonged shading.

Panel tracking: It is the technology that optimizes the angle at which solar panels receive sunlight. The trackers are mounted beneath solar panels to adjust their position following the sun's movement, to maximize energy absorption. The integration of panel tracking systems, while increasing mechanical complexity and cost, offers dynamic control over both energy yield and light availability for crops. These trackers can be either single-axis, or dual-axis which have been discussed below in detail.

- **Single-Axis Tracking:** This tracker rotates the panel typically along north-south axis, involves panels rotating tracking the sun's azimuth. This can significantly increase energy generation by 15-25% compared to fixed-tilt systems. For agriculture, single-axis trackers can be programmed to optimize light distribution for crops. For instance, in the morning and evening, panels can be tilted to allow more direct sunlight to reach the crops, while during peak midday hours, it might be adjusted to provide partial shading, mitigating heat stress for shade-tolerant or susceptible crops.
- **Dual-Axis Tracking** This tracker rotates the panel across both the axis to track both the sun's azimuth and elevation, maximizing energy capture by up to 30-35%. While offering the highest energy output, complex movement patterns must be carefully managed to avoid prolonged or excessive shading of crops. Algorithms can be developed to balance energy generation with crop light requirements, potentially by programming specific shading patterns or maintaining a certain minimum light threshold on the agricultural land. The increased height and movement of dual-axis systems also necessitate more robust structural designs to withstand wind loads.

Ground clearance: Ground clearance, defined as the vertical distance between the lowest point of the PV array and the ground, is a critical design parameter that directly impacts agricultural operations and microclimatic conditions as mentioned in the following:

- **Agricultural Accessibility:** Sufficient ground clearance is essential to accommodate agricultural machinery (tractors, harvesters, irrigation equipment) and facilitate manual labour. The specific height will vary depending on the type of crops cultivated (e.g., row crops vs. orchards) and the equipment employed. Inadequate clearance can severely restrict farming practices.
- **Microclimatic Impact:** Higher ground clearance generally allows for better air circulation, reducing humidity and heat build-up beneath the panels, which can be beneficial in tropical or semi-arid environments. It also allows for more uniform light distribution over a wider area. However, excessive clearance can lead to increased structural material costs and reduced shading benefits for shade-benefiting crops.



Inter row spacing:

Inter-row spacing, which is the horizontal distance between adjacent rows of PV arrays, is paramount for optimizing light distribution, facilitating agricultural access, and managing microclimates. The impact of inter row spacing on light distribution, agricultural operations and microclimate is discussed in the following:

- **Light Distribution:** Wider inter-row spacing allows more direct sunlight to reach the ground between rows, benefiting sun-loving crops. Conversely, narrower spacing provides greater shading, suitable for shade-tolerant or shade-benefiting crops, or for mitigating heat stress in arid environments. The sun path diagram analysis is crucial in determining the inter-row spacing. It is also based on the PAR requirements of different crops and desired level of shading.
- **Agricultural Operations:** Adequate spacing is necessary to allow for the passage of agricultural machinery, ensuring efficient planting, cultivation, irrigation, and harvesting. The turning radius of machinery, adequate right of way, and operational safety must be factored into the design.
- **Microclimatic Influence:** Inter-row spacing, in conjunction with array height and tilt, influences wind flow and humidity levels between rows. Wider spacing can enhance air circulation, while narrower spacing, combined with lower ground clearance, can create more humid and cooler microclimates.

The details of the calculation of the parameters are provided in Appendix C2.

3.3.3 Bifacial Gain & Albedo

Bifacial PV modules generate additional energy by capturing reflected solar radiation on the rear side of the module. As a result, ground-surface characteristics play an important role in determining bifacial gain. Surfaces with higher albedo, such as light-coloured exposed soils or light-coloured vegetation, reflect a greater proportion of incoming solar radiation and can increase rear-side irradiance, thereby improving bifacial energy yield. In contrast, darker soils or dense vegetation can absorb more incident radiation and exhibit lower reflectivity, resulting in reduced rear-side irradiance and lower bifacial gain. Therefore, in AgriPV systems, the type of vegetation, crop selection, and canopy density influence ground albedo and can affect the magnitude of bifacial performance benefits. While elevated module configurations can enhance rear-side exposure, the overall bifacial gain will depend on the reflectivity of the underlying surface, whether it is exposed soil or vegetative cover.

3.3.4 Electrical system, safety and technical considerations

This section delves into other PV system considerations such as safety, cabling, inverters, battery energy storage system (BESS), transformer, and metering arrangements. These considerations ensure electricity production from AgriPV system in safe and reliable manner.

a. Safety considerations

Safety forms the foundational tenet of any complex electrical installation, and its criticality is amplified within the dynamic and operational environment of AgriPV systems. Prudent risk management and adherence to international best practices are necessary to protect personnel, livestock, and solar PV project assets.

Electrical safety: Comprehensive electrical safety protocols are imperative during the installation and operational phases of an AgriPV project. This requires the implementation of the following considerations:

- **Proper Grounding** will help to effectively mitigate electrical shock hazards and protect equipment from transient over voltages. Providing **redundant grounding** (multiple independent grounding paths for electrical equipment) helps in creating a highly reliable grounding system. Grounding of AgriPV system should be carried out in accordance with IEC 60364 series as voltages of panel array are typically less than 1500 V DC.
- The selection and installation of appropriately rated **overcurrent protective devices** (fuses and circuit breakers) should be conforming to IEC 60947 series (Low-voltage switchgear and control gear). This is essential to safeguard the AgriPV system from fault currents such as due to short circuit faults.

- There should be **accessible and clearly designated isolation switches** for both DC and AC circuits of AgriPV system. These switches should be coupled with stringent Lockout/Tagout (LOTO) procedures (ensuring all potential energy sources are isolated with lockout device to render them inoperative and tagging of lockout device with appropriate warning tag and reason for lockout). LOTO procedures are critical during maintenance to prevent inadvertent re-energization and safety of maintenance staff and equipment.

Mechanical safety: The mechanical integrity of the PV mounting system is a necessary requirement, particularly given the co-location with agricultural activities.

This involves the following considerations:

- Structures must be engineered for **long-term resilience** against anticipated environmental loads in the region such as high winds, dust storms, and snowfall. Guidance for the design can be taken from IEC 61215 series for panel design qualification.
- Design considerations should incorporate **adequate clearances** beneath and around PV arrays to facilitate the safe and unobstructed movement of agricultural machinery (e.g., tractors, harvesters), irrigation systems, and personnel.
- All fastenings, including bolts, clamps, and structural connections, must be **securely torqued** to manufacturer specifications and subjected to periodic inspection to prevent loosening due to vibration or environmental stressors.

Operational Safety: Operational safety is critical due to the constant interaction between agricultural activities (e.g., heavy machinery, irrigation) and electrical infrastructure.

The following considerations are necessary from an operational safety perspective:

- **Comprehensive training** on operational safety should be provided for all personnel working in the vicinity of AgriPV system including farmers and O&M staff. Personnel should be properly sensitized to the risks and hazards that could arise from AgriPV system along with procedures to follow in case of any accident. This will help minimize the damage to personnel, livestock, and equipment.
- Prominent, durable, and universally understood **warning signage**, conforming to relevant safety signage standards, must be strategically positioned throughout the site to clearly indicate potential hazards.
- Proactive measures for **fire safety** should be carried out, particularly around inverters and battery storage units. Appropriate fire suppression equipment (e.g., CO_2 or clean agent extinguishers) should be readily available at the site.

b. Cabling considerations

Cabling constitutes the critical conductive pathway for electricity transmission within AgriPV system. Cabling ensures flow of electrical power from panels to inverters and subsequently to the grid or local loads. Within the dynamic and often challenging agricultural context, cables are exposed to unique environmental and operational stresses. Current magnitude, voltage drop and losses and environmental conditions are the primary consideration one must do while sizing the cable. There is need for judicious selection, robust installation, and rigorous maintenance for cabling within AgriPV system. There are two primary types of cabling within AgriPV project:

DC Cabling (Panel to Inverter): The precise sizing of DC conductors is determined by the following factors: (a) the anticipated current magnitude, (b) permissible voltage drop, (c) the prevailing ambient temperature. The selection of DC cabling should be carried out in accordance with IEC 60364-7-712 (Requirements for special installations or locations - Solar photovoltaic (PV) power supply systems).

The use of UV-resistant, outdoor-rated, double-insulated PV-specific cables (e.g., certified to EN 50618 or equivalent IEC standards like IEC 62930) can be helpful in outdoor environments as observed in AgriPV system. Further, high-quality, weather-tight connectors (e.g., MC4-compatible, adhering to IEC 62852 (Connectors for DC application in photovoltaic systems) should be used for maintaining robust electrical connections and preventing moisture ingress (moisture ingress can lead to hazardous arc faults).

AC Cabling (Inverter to Transformer/Grid): Analogous to DC cabling, AC conductor sizing must account for current capacity, permissible voltage drops, and environmental conditions, adhering to IEC 60364 series and local electrical codes. Appropriate outdoor-rated AC cables with robust insulation (e.g., XLPE insulated, compliant with IEC 60502 series for power cables) as per suitability for the specific voltage and current levels should be considered. These cables should also be protected within conduits or be of armoured construction, particularly for underground cables, to ensure longevity and safety.

Cable routing: Cable routing refers to the path that electrical conductors (cables) traverse from their origin (e.g., PV panels) to their destination (e.g., inverters, transformers, or the grid connection point). The consideration for cable routing is as follows:

- **Underground** cables within appropriate, durable conduit (e.g., rigid PVC or HDPE, compliant with IEC 61386 series for conduit systems) is generally preferred method for cable routing in AgriPV system. Underground cables offer superior physical protection against agricultural machinery, rodent gnawing, and UV degradation.
- **Proper trenching** depth, as per local civil engineering standards, and the inclusion of warning tape are critical for safety and future excavation awareness.
- Where **above-ground routing** is considered, cables must be securely installed within UV-resistant conduits or cable trays, elevated sufficiently to prevent interference with agricultural activities, and protected from mechanical abrasion.
- **Adequate strain relief** at all termination points and connections is vital to prevent conductor damage from tension or repetitive bending.

c. Inverter considerations

The inverter serves as the sophisticated interface of an AgriPV system converting the direct current (DC) electricity generated by PV panels into alternating current (AC) electricity suitable for grid interconnection or direct consumption. Its judicious selection influences system efficiency, reliability, and grid integration capabilities. The different inverter typologies are explained as follows:

- **Microinverters:** Microinverters perform DC-to-AC conversion at the individual panel level. The impact of panel mismatch (due to shading of panel, characteristics mismatch) is avoided as there is no impact of one panel on another and each panel operates at its own maximum power point (voltage and current from panel at which maximum power gets generated from panel). This helps in maximizing energy harvest at the panel level and provides granular monitoring capabilities, albeit often at a higher capital expenditure.
- **String Inverters:** These inverters convert DC power from multiple series-connected panels (strings) into AC power. String inverter operates the panel array at voltage and current at which maximum power is generated from the panel array. The aggregate performance of string inverter gets disproportionately affected in case of panel mismatch reducing the power output from the string.
- **Hybrid Inverters:** Essential for systems incorporating battery energy storage, hybrid inverters possess the advanced functionality to seamlessly manage both grid-tied PV operation and efficient battery charging/discharging, enabling sophisticated load shifting, critical backup power provision, and potential participation in grid ancillary services.

The key considerations for inverter in AgriPV project are shown in Figure 25 and explained as follows:

Figure 25: Considerations for inverter in context of Agriphotovoltaics



- **Conversion Efficiency:** High conversion efficiency (typically ranging from 95% to 99% for modern designs) is necessary, as it directly minimizes energy losses during the DC-to-AC conversion process, thereby maximizing the overall system output and contributing to the financial viability.
- **Maximum Power Point Tracking (MPPT) Capability:** The inverter's ability to continuously track and operate at the Maximum Power Point (MPP) of the PV array is critical for optimizing energy harvest under dynamic irradiance and temperature conditions. Multiple MPPT inputs are highly advantageous for

arrays with anticipated partial shading pattern as it helps in improving the energy yield.

- **Environmental Rating:** Inverters deployed in AgriPV settings must possess a robust Ingress Protection (IP) rating (e.g., IP65 or higher, as per IEC 60529 (Degrees of protection provided by enclosures (IP Code))) to ensure resilience against dust, moisture, and temperature extremes inherent in outdoor agricultural environments.
- **Grid Code Compliance:** Strict adherence to local utility grid codes and interconnection requirements (e.g., voltage and frequency regulation, reactive power control, low voltage ride-through capabilities, as stipulated by IEC 62109 series (Safety of power converters for use in photovoltaic power systems) and local grid operator mandates) is necessary for seamless and compliant grid integration.
- **Monitoring and Communication:** Advanced remote monitoring capabilities in inverter (e.g., via Modbus, Ethernet, or wireless protocols) are crucial for real-time performance tracking, proactive fault detection, predictive maintenance scheduling, and optimized operational management without necessitating frequent on-site visits, aligning with ISO 50001 (Energy Management Systems) principles.
- **Reliability and Warranty:** Inverters from reputable manufacturers with established track records, robust quality control processes (e.g., ISO 9001 certified), and comprehensive warranty provisions helps in ensuring long-term system dependability.

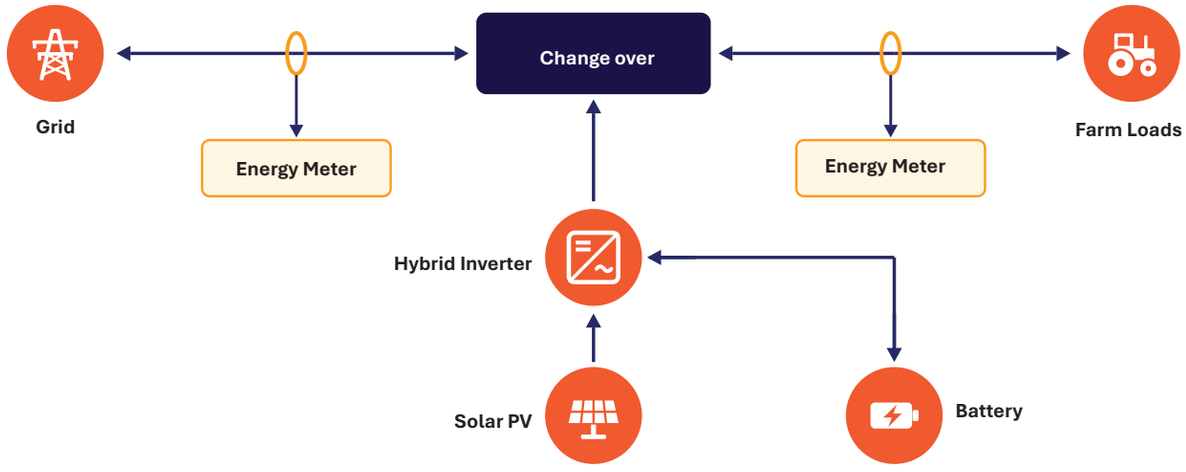
d. Battery Energy Storage Systems (BESS) considerations

BESS can substantially enhance energy independence for the farm, providing vital grid stability services for power utility company, and enabling novel revenue streams for the developer. The schematic for BESS within AgriPV setup is shown in Figure 26.

The technology considerations for BESS are as follows:

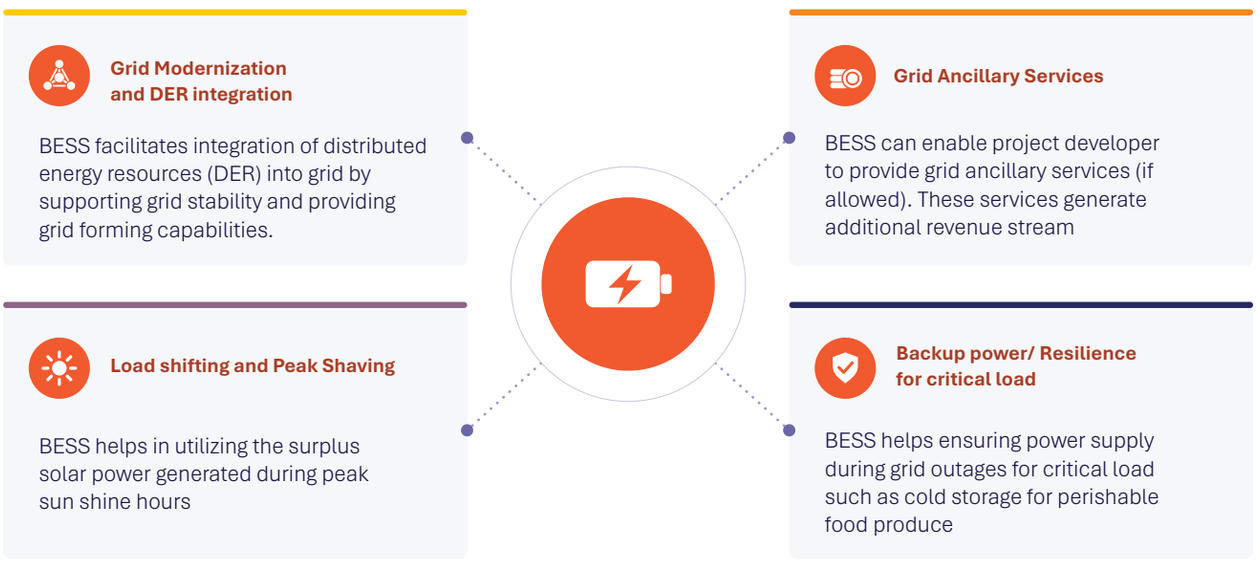
- **Dominant Chemistry:** The current dominant chemistry for grid-scale and commercial BESS is Lithium-ion, particularly Lithium Iron Phosphate (LiFePO4). LiFePO4 offers excellent energy density, a high number of charge/discharge cycles (typically 6,000 to 10,000 cycles to 80% Depth of Discharge (DoD), enhanced thermal stability, and a lower risk of thermal runaway compared to other lithium-ion variants. Other emerging chemistries like Sodium-ion are gaining traction for stationary storage due to lower material costs and abundant resources, though their energy density is currently lower than Li-ion.
- **Round-Trip Efficiency (RTE):** The Li-ion BESS typically achieve a round-trip efficiency (RTE) of 85% to 95%. This metric represents the ratio of the energy discharged from the battery to the energy put into it during charging. Higher RTE signifies less energy loss during the storage cycle, directly impacting the economic viability of the system.

Figure 26: Schematic for BESS within AgriPV setup



- **Power and Energy Density:** Continuous advancements are leading to higher power and energy densities, allowing for more compact battery installations and increased energy storage capacity within a given footprint.

Figure 27 Use cases for BESS in AgriPV setup



The integration of a Battery Energy Storage System (BESS) can significantly augment the economic and operational value proposition of an AgriPV system. The principal use cases for BESS in AgriPV projects are illustrated in Figure 27 and described below

- **Load Shifting and Peak Shaving:** This is a primary use case for BESS within AgriPV system. Surplus solar energy generated during periods of high irradiance (e.g., midday peaks) is stored using BESS for strategic discharge during periods of high demand (e.g., evening) or when solar generation is low. This capability significantly improves grid reliability and reduces strain during peak load hours and peak sunshine hours for the grid operator. Further, for consumer (for whom time of day tariff from power utility is applicable), it reduces reliance on grid power during expensive tariff windows and effectively mitigates peak demand charges from the utility, thereby optimizing operational expenditure for the consumer.
- **Backup Power/Resilience for Critical Loads:** BESS provides critical power to essential agricultural loads (e.g., irrigation pumps for uninterrupted water supply, climate control systems in polyhouses, cold storage facilities for perishable produce, livestock watering systems, automated feeding systems) during grid outages or scheduled grid curtailments. This ensures operational continuity for the farm, minimizes potential economic losses associated with interruptions, and enhances food security by harvesting the crop at proper time.
- **Grid Ancillary Services and Revenue Generation:** Depending on regional regulatory frameworks and market opportunities, BESS can also actively participate in grid ancillary services. This includes frequency regulation (balancing grid frequency by rapidly injecting or absorbing power), voltage support (maintaining stable voltage levels), or demand response programs (reducing consumption during peak grid stress). These services can generate additional revenue streams for the AgriPV project, improving the overall project economics.
- **Grid Modernization and Distributed Energy Resource (DER) Integration:** BESS facilitates the smoother integration of intermittent renewable energy sources like solar into the grid. It can provide grid-forming capabilities in isolated microgrids or support grid stability in weak grid areas, making AgriPV projects valuable assets for grid modernization initiatives.

The key considerations for BESS in AgriPV project are shown in Figure 28 and explained as follows:

Figure 28: Considerations for BESS in context of AgriPV



- **Battery Chemistry:** As discussed above, LiFePO4 is prevalent. Adherence to IEC 62619 (Safety requirements for secondary lithium cells and batteries for use in industrial applications) is crucial.
- **Capacity (kWh) and Power (kW):** The energy capacity of the BESS must be precisely sized based on the specific energy demands to be met, the desired discharge duration, and a thorough economic viability assessment (e.g., through detailed load profiling). The power rating dictates the maximum instantaneous rate at which energy can be discharged or charged, which must correspond to peak load requirements.
- **Battery Management System (BMS):** A sophisticated and robust BMS is indispensable for continuous monitoring and precise management of individual battery cell voltages, temperatures, currents, and states of charge. This ensures safe operation, optimizes performance, prevents overcharge/discharge, and significantly extends battery lifespan, aligning with IEC 62485 series (Safety requirements for secondary batteries and battery installations).
- **Integration with Inverter:** Seamless and intelligent communication protocols between the BESS, its BMS, and the hybrid inverter are paramount for efficient charge/discharge cycling, optimal energy flow management, and overall system synchronization.
- **Thermal Management:** Batteries operate optimally within a specific temperature range. Consequently, adequate thermal management systems (e.g., active cooling, heating, or passive ventilation) are required to maintain operating temperatures within manufacturer specifications, particularly in regions experiencing extreme ambient temperatures, to preserve battery performance, extend longevity, and ensure safety.
- **Safety and Enclosure:** The BESS must be housed in a secure, purpose-built, well-ventilated, and fire-resistant enclosure, often incorporating dedicated fire suppression systems (e.g., as per NFPA 855 (Standard for the Installation of Stationary Energy Storage Systems) or local fire codes), to mitigate risks associated with thermal events or off gassing. Proper end-of-life management and recycling protocols are also critical for environmental safety.

PV system sizing in AgriPV projects is driven primarily by the structural design and spatial layout adopted to accommodate both power generation and agricultural activities. Unlike conventional ground-mounted solar plants, where capacity is maximized within a given land parcel, AgriPV projects must balance installed PV capacity with crop requirements, machinery access, and microclimate objectives. The structural configuration therefore determines how many modules can be installed per unit area, how they are arranged, and the resulting direct current (DC) capacity of the system, which in turn informs the alternating current (AC) capacity and grid interconnection design.

3.3.5 AC capacity and DC/AC ratio

The Alternating Current (AC) capacity of an AgriPV project refers to the aggregate rated power output of the inverters. These inverters are critical components responsible for converting the Direct Current (DC) electricity generated by the PV panels into AC electricity, which is suitable for grid connection and direct consumption by local loads.

It is a common practice to maintain the AC capacity at a level lower than the DC capacity. This intentional oversizing of the DC array relative to the inverter capacity (known as DC/AC ratio or inverter loading ratio) is implemented to ensure that inverters operate closer to their peak efficiency for extended periods. While the DC array might have a higher nominal capacity, it rarely operates at 100% of its rated power due to various factors such as temperature, shading, and panel degradation. By having a DC/AC ratio greater than 1, the inverters are typically operating in their optimal power band, thus maximizing the overall AC energy yield from the solar PV project over its operational lifetime.

The DC/AC ratio typically ranges from 1.1 to 1.4, with larger-scale projects often favouring values at the higher end of the range to maximize energy harvesting and optimize inverter utilization. In some smaller-scale projects, however, lower DC/AC ratios, including values close to 1.0, may be adopted due to economic considerations, inverter sizing constraints, or specific load requirements.

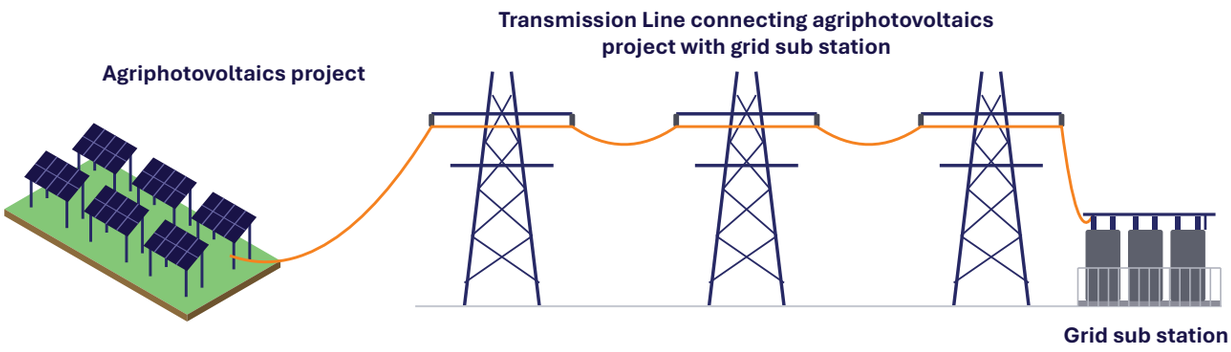
3.3.6 Grid connectivity and deployment considerations

The optimal scale of an AgriPV project is closely linked to the available grid infrastructure and intended power offtake model. In India, policy support for agricultural solarisation has evolved around two broad approaches: distributed generation connected to local agricultural feeders and substations, and behind-the-meter applications serving on-farm loads such as irrigation pumps, cold storage facilities, and agricultural processing units. These approaches have distinct capacity, connectivity, and revenue implications.

In rural/countryside regions (predominantly agricultural settlements), AgriPV projects aim to offer a dual benefit: (a) enhancing energy access and (b) improving the reliability of electricity supply for local communities. However, integration of these projects into the existing electrical grid, particularly with agricultural feeders, necessitates careful consideration of grid injection limitations as follows:

- **Grid Operator Specifications:** The grid operator imposes limit on maximum power injection at substations. This restriction is crucial for maintaining operational reliability, ensuring grid stability, and preventing localized overloads. This maximum power limit leads to setting up of AgriPV system of a capacity lower than this limit in the vicinity of that substation. Exceeding this limit can lead to voltage fluctuations, frequency deviations, and equipment damage, jeopardizing the integrity of the grid.
- **Transmission Infrastructure and Right-of-Way:** Connecting AgriPV projects to a grid substation in most of the cases requires the construction of new transmission lines. The illustration for transmission line for connecting AgriPV project with grid substation is shown in Figure 29.

Figure 29: **Illustration for transmission line for connecting AgriPV project with grid substation**



Securing the right-of-way (ROW) for these transmission lines presents significant challenges as follows:

- **Public Support:** Addressing community concerns and gaining public acceptance for the transmission lines.
- **Statutory Clearances:** Obtaining various permits and approvals from governmental and environmental agencies.
- **Land Acquisition:** Acquiring necessary land parcels for transmission line corridors.
- **Topographical and Land Use Challenges:** Navigating diverse terrains and existing infrastructure, including roads, railways, and rivers, which can significantly increase project complexity and costs.

While the preceding design considerations are broadly applicable across geographies, project capacity and grid-connection decisions are also shaped by national and sub-national electricity regulations.

The design considerations presented in this chapter establish the core technical and agricultural parameters that govern AgriPV system configuration, from crop requirements and shade tolerance to mounting height, spacing, orientation, structural considerations, electrical integration, and grid connectivity. These parameters are interdependent and cannot be optimized independently of the climatic and agricultural context. The next chapter applies this design foundation to the five priority climatic zones identified in Chapter 1, translating the general principles into climate-specific considerations for site assessment, crop selection, system configuration, resource management, and operational risk mitigation.



CHAPTER 04

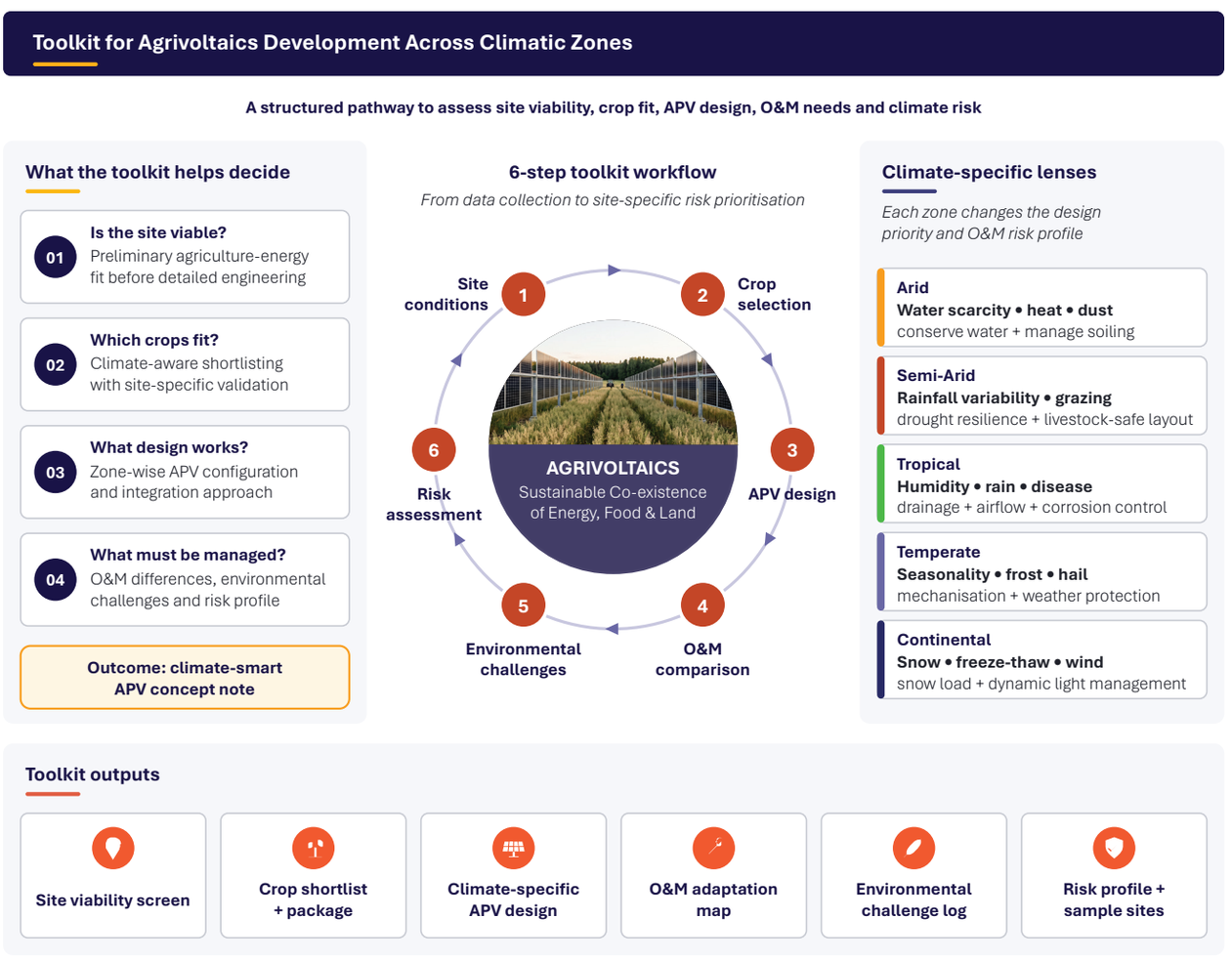
Climate-Zone AgriPV Development Toolkit



The climatic and agricultural context strongly influences the feasibility, design, operation, and performance of AgriPV systems. Differences in temperature, rainfall, humidity, solar radiation, wind, water availability, soil conditions, and agricultural practices affect both crop performance and PV system design. Building on the climatic classification established in Chapter 1 and the agricultural and technical considerations discussed in Chapter 3, this chapter translates these factors into a climate-responsive toolkit for assessing site suitability, selecting crops, designing AgriPV systems, and identifying key operation, maintenance, and environmental risks across five priority climatic zones: Arid, Semi-Arid, Tropical, Temperate, and Continental.

The toolkit follows a sequential decision pathway as shown in Figure 30. It begins with site suitability assessment to establish whether the agricultural and physical characteristics of a site are compatible with AgriPV development. This is followed by climate-responsive crop selection, which identifies crops that can perform within the expected AgriPV microclimate while remaining compatible with farming operations. The resulting site and crop considerations then inform climate-specific system design and integration. The framework subsequently considers operation and maintenance requirements, environmental and social challenges, and risk assessment, before examining grid connectivity and deployment models.

Figure 30: A Structured toolkit for AgriPV Development across different agro-climatic zones



Disclaimer: Use as preliminary decision-support: not a substitute for detailed engineering, site surveys, agronomic trials or statutory approvals.

4.1 Site Suitability Assessment

The objective of the site suitability assessment is to determine whether a specific land parcel, farm cluster, or target area is suitable for an indicative AgriPV configuration. The assessment establishes whether there is reasonable compatibility between agricultural production and PV development and whether sufficient evidence exists to proceed to detailed engineering and feasibility assessment. The assessment focuses on site-specific physical, agricultural, technical, environmental, and operational parameters that determine constructability and compatibility between agricultural activities and the proposed PV system. Key areas of evaluation include:

- Site conditions, terrain, and existing land use
- Crop characteristics and associated machinery movement
- Water access, soil quality, and solar resource availability
- Obstructions, site access, grid proximity, and power evacuation assumptions

The site assessment follows a six-step sequence (described in Table 33), moving from confirmation of the site boundary and existing agricultural use to physical, solar, electrical, and farming–PV compatibility assessments, and finally to a suitability rating and confidence level.

Table 33: Technical Focus Areas for Site Suitability Assessment for AgriPV installation and configuration

Step	Action / Focus Area	Description / Key Activities
1	**Confirm Site Boundary**	The process begins with the precise confirmation of the site boundary or coordinates. If only a broad region is available, the output must be explicitly marked as a "regional screening" rather than a site-specific assessment.
2	**Establish Agricultural Use**	A thorough understanding of the current agricultural context is required. This includes the crop calendar, typical crop height, row spacing, machinery used, irrigation practices, and key seasonal operations.
3	**Assess Physical Conditions**	Evaluate tangible site conditions, including slope, terrain, drainage patterns, flooding risk, physical access routes, nearby obstructions, soil characteristics, and any land-use restrictions.
4	**Assess Solar and Electrical Conditions**	Concurrently, evaluate solar and electrical factors by assessing irradiance data, potential shading, grid proximity with a likely evacuation path, and the state of existing infrastructure.
5	**Check Farming & PV Compatibility**	A critical step involves checking the direct compatibility between farming operations and a potential PV layout. This includes necessary clearances for machinery, inter-row spacing, O&M access, and overall farm equipment circulation.
6	**Assign Suitability Rating**	The assessment culminates in a formal suitability rating and a corresponding confidence level, carefully separating confirmed findings from those inferred through remote sources or stakeholder inputs.

A robust site assessment requires a minimum set of data to ensure that conclusions are not based on unsupported assumptions. The following Table 34 outlines the essential data categories, preferred sources, and their role in the assessment. This multidisciplinary data pack provides the evidence base for evaluating the preliminary technical and agricultural suitability of an AgriPV project.

Table 34: Minimum Data Requirements for Site Suitability Assessment for AgriPV installation and configuration[56]

Category	Parameter	Why is it critical for AgriPV	How to assess it (tools & methods)
Geotechnical & Topography	Soil Characteristics	Determines foundation stability and crop suitability (rooting depth, water-holding, fertility).	Geotechnical borings and lab tests (texture, compaction, bearing capacity); agronomic soil tests.
	Topography & Slope	Affects erosion risk, machinery access, irrigation layout, and panel row layout.	Detailed topographic survey or DEM (drone/LiDAR, GPS survey).
	Subsurface Conditions	Bedrock, shallow water table or cavities can limit foundations and deep-root crops.	Geotechnical report, test pits, and ground-penetrating radar (GPR) to map subsurface layers.
Hydrology	Water Source & Rights	Reliable, legal water supply is essential for irrigation and long-term farm viability.	Review water rights, permits, well logs; consult water authorities and farmer records.
	Water Quality	Salinity, pH, and contaminants affect crop yields and corrosion of metal structures.	Laboratory water analysis (EC, pH, ions, metals); periodic sampling of wells/surface water.
	Drainage & Flood Risk	Poor drainage harms crop and increases risk to electrical equipment in flood-prone areas.	Topographic analysis, soil drainage class, flood maps (e.g., FEMA) and local flood history.
Meteorology	Solar Resource	Determines energy yield and economic viability of the AgriPV system.	Long-term solar datasets (e.g., NSRDB), satellite data, and PV modeling tools (e.g., PVSyst).
	Wind & Snow Loads	Extreme loads affect structure stability and potential damage to crops and equipment.	Local building codes, ASCE load maps, and long-term meteorological station data.
	Local Weather Hazards	Hail, frost, heat waves, storms influence crop choice and the protective value of panels.	Historical weather records, crop loss reports, and farmer interviews.
Agriculture	Existing Soil Health	Baseline fertility and organic matter guide nutrient, amendment, and cover-crop plans.	Agricultural soil testing (NPK, organic matter, pH, micronutrients) and visual soil assessment.
	Existing Biota	Weeds, pests, pollinators, and soil life affect pest control and biodiversity goals.	Field walk-through with agronomist/ecologist; vegetation surveys and pest monitoring.



56 ***Limitations/Disclaimers*** The quality of the assessment is directly dependent on the accuracy of the sourced data. Data provided by third parties should be cross-checked where possible. This data pack represents a minimum requirement for a preliminary assessment and is not sufficient for detailed engineering or a bankable feasibility study.

Table 34: (continued) Minimum Data Requirements for Site Suitability Assessment for AgriPV installation and configuration

Category	Parameter	Why is it critical for AgriPV	How to assess it (tools & methods)
Infrastructure	Site Access	Access for machinery affects installation costs and routine farm operations under panels.	Visual inspection, road condition survey, and review of local road maps/transport restrictions.
	Grid Interconnection	Distance and capacity of nearby grid connection affect project cost and scalability.	Consultation with local utility; review of grid maps, substation capacity, and interconnection rules.
	Obstructions	Legal or physical "no-build" zones constrain layout for panels and farm operations.	Official land survey, title search, zoning maps, and environmental/utility easement checks.

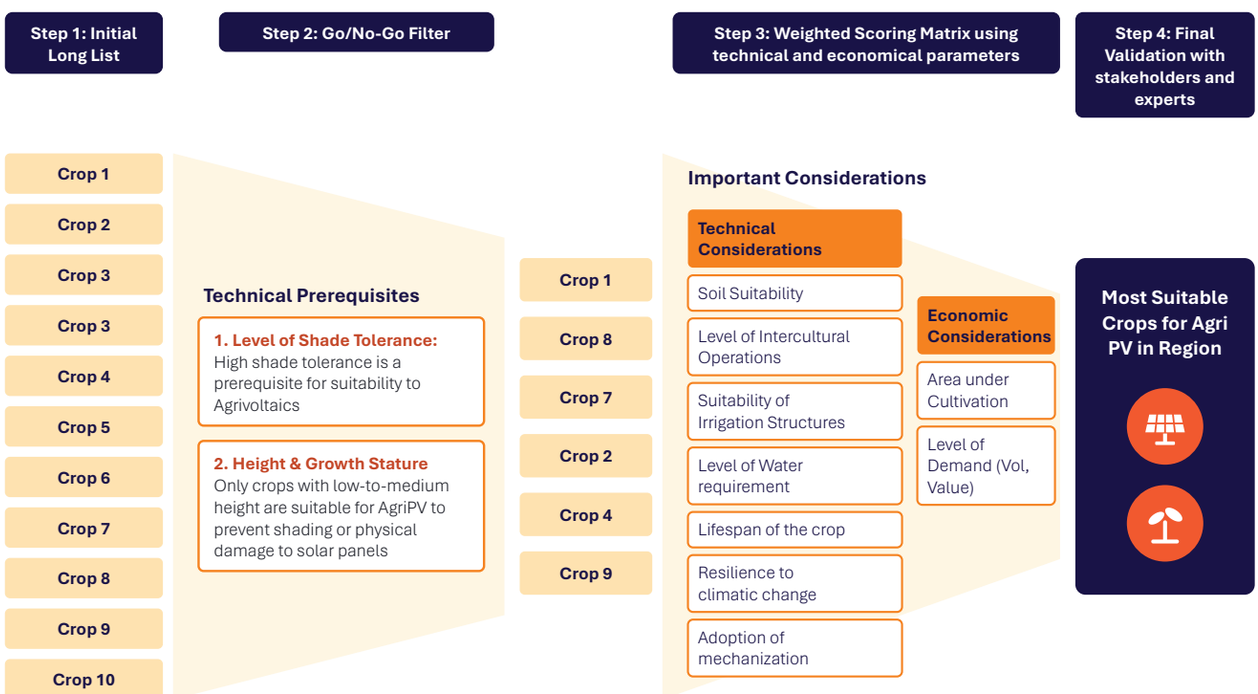
Remote Assessment Workflow: Remote assessment is a cost-effective first step for initial screening, pre-visit preparation, or when physical visits are not immediately possible. It follows a structured workflow to build an initial evidence base for the site. The process includes mapping the boundary, overlaying land-use datasets, assessing terrain using DEM (Digital Elevation Model) sources, estimating solar resources with standard tools, and reviewing historical imagery for changes. All assumptions derived from this process should be logged and assigned a confidence level. A detailed description of the remote assessment workflow is provided in Appendix C.



4.2 Climate-Responsive Crop Selection for AgriPV

The primary objective of crop selection for AgriPV is to identify crops that can perform under the modified light, temperature, and moisture conditions created by the PV system while remaining compatible with farming operations and economically relevant to the site (as discussed in Figure 31). Crop selection is therefore not solely an agronomic decision; it requires balancing crop requirements with the proposed PV configuration, site conditions, resource availability, farming practices, and local market conditions. This section provides a systematic, data-driven methodology for identifying and prioritising suitable crops across the five climatic zones: Arid, Semi-Arid, Tropical, Temperate, and Continental. The methodology should be used as a decision-support tool and complemented by site-specific agronomic validation.

Figure 31: The Four-Step Crop Selection Process[57,58]



The four-step process described in Table 35 first establishes a technically feasible crop shortlist. The shortlisted crops are then evaluated using a structured scoring matrix to compare their technical, operational, and economic suitability within the proposed AgriPV system.

57 This approach is strictly a crop-selection and prioritization guide for the site assessment phase. It is not a detailed agronomy prescription, a specific seed or variety recommendation, financial appraisal, a Detailed Project Report (DPR), a structural design, or a procurement specification. Those activities are considered downstream work that would follow this initial assessment.

58 Source: PwC Analysis and Stakeholder Consultations



Table 35: Four-Step Climate-Responsive Crop Selection Process

Stage	Key question	What the user should do	Output
Step 1: Initial longlist	What crops are already grown or realistically grown near the site?	Compile crops from local agriculture data, farmer consultations, mandi/market information, and local agronomists.	Long list of crops relevant to the site or farm cluster.
Step 2: Go/ No-Go filter	Which crops are technically incompatible with the proposed PV layout?	Remove crops that fail the minimum requirements for shade response, crop height/canopy, machinery clearance, irrigation practicality or basic site fit.	Shortlist of technically feasible crops.
Step 3: Scoring matrix	Among feasible crops, which ones offer the best technical and economic fit?	Score each crop on agreed parameters using evidence and stakeholder input. Adjust weightages to match site context and climate risk.	Ranked list of candidate crops with scores and assumptions.
Step 4: Validation	Which crop choices are robust enough to recommend for the site?	Review the ranking with local agronomists, farmers, and project designers. Validate against site specifics before recommending.	Final crop recommendation or conditional shortlist.



The Crop Suitability Matrix provides a structured method for comparing and prioritising crop options within a location-specific AgriPV system. It should be applied after the initial Go/No-Go screening has confirmed that candidate crops meet the basic technical compatibility requirements.

The technical prerequisites filter is a Go/No-Go stage (as shown in Table 36). **Crops that do not meet these basic conditions should not move to the scoring matrix unless the project is explicitly considering experimental trials**.[59]

Table 36: Technical prerequisites for crop selection in AgriPV configurations

Technical prerequisite	What it means in simple terms	How to apply it
Shade Tolerance	The crop should be able to grow under the expected partial shade created by the PV structure without unacceptable yield or quality loss.	Check crop physiology, local experience, available studies and expert views. If the crop is highly light-demanding and no supporting evidence exists, treat it at high risk.
Height	The crop height and canopy form should be compatible with the proposed panel clearance, row spacing, farm access and O&M requirements.	Compare expected crop height and canopy spread with module height, inter-row spacing, machinery movement and safety clearance.

Approach for assessing crop suitability using technical, agricultural, operational, and economic considerations:[60]

- **Adjust weightages:** Customize the "Weightage" column to match your project's goals (e.g., prioritize water savings, market value, or mechanization).
- The weightings presented in Table 37 are illustrative and should be adjusted to reflect the objectives, constraints, and stakeholder priorities of the project under assessment. The same scoring framework can therefore be applied across climatic zones while allowing the relative importance of individual criteria to vary.
- **Score each crop:** Rate each candidate crop from 1 (Very Poor Fit) to 5 (Excellent Fit) against each parameter.
- **Calculate and compare:** The weighted score provides a basis for ranking the shortlisted crops. The highest-scoring crop should not automatically be considered the final recommendation; the ranking should be reviewed against site-specific constraints and validated with relevant agronomic, farming, technical, and market stakeholders.

59 Important disclaimer — Passing the Shade Tolerance and Height filters does not automatically make a crop suitable. It only means the crop can be taken to the next stage for more detailed technical and economic scoring

60 Recommended wording — The crop with the highest weighted score may be considered the preferred candidate for further validation, subject to site-specific agronomic review, farmer consultation, market assessment and confirmation of the proposed PV configuration.

Table 37 Illustrative Crop Suitability Matrix for AgriPV

							Illustrative
Category	**Parameter**	**Brief Explanation**	**Weightage (%)**	**Crop A: Leafy Green** **Score (1-5)**	**Crop A Weighted Score** **Weighted Score**	**Crop B: Root Vegetable** **Score (1-5)**	**Crop B Weighted Score** **Weighted Score**
Technical considerations	**Climate and Weather Tolerance**	Tolerance to the site's expected temperature extremes, rainfall variability, heat, frost, wind, and other relevant climatic stresses, including the extent to which AgriPV may moderate these conditions.	**20%**	**5**	100	4	80
	Ease of Mechanization	How compatible the crop is with machine-based farming for scalability.	**15%**	**3**	45	5	75
	Water & Irrigation Needs	The crop's water requirements and how well it leverages panel shade to improve water efficiency.	**15%**	**5**	75	3	45
	Crop Cycle and Rotation Compatibility	Suitability for being planted in sequence or alongside other crops to benefit soil health.	**5%**	**4**	20	3	15
	Labour Intensity	The amount of manual work required for cultivation and harvesting.	**5%**	**2**	10	3	15
	Lifespan of the Crop	Whether it's an annual or perennial, affecting how often soil is disturbed.	**5%**	**3**	15	4	20
Economic Considerations	**Level of Demand (Value)**	The market for the crop, especially its price per unit (high value vs. commodity).	**25%**	**5**	125	4	100

Table 37 (continued) Illustrative Crop Suitability Matrix for AgriPV

						Illustrative	
Category	**Parameter**	**Brief Explanation**	**Weightage (%)**	**Crop A: Leafy Green** **Score (1-5)**	**Crop A Weighted Score** **Weighted Score**	**Crop B: Root Vegetable** **Score (1-5)**	**Crop B Weighted Score** **Weighted Score**
	Area Under Cultivation	The existing scale of the crop in the region, indicating established markets and knowledge.	**10%**	**3**	30	4	40
Totals			**100%**		**420**		**385**

Illustrative conclusion: Crop A (Leafy Green) achieves a higher weighted score than Crop B (Root Vegetable), primarily because of its stronger performance against the assumed climate and market criteria. This result is illustrative and should not be interpreted as a universal crop recommendation. Final crop selection should be based on site-specific agronomic validation, farming practices, market conditions, and the final AgriPV system configuration.

The relative importance of crop-selection criteria is not static; it changes with the agricultural challenges, opportunities, and project objectives of a given climatic and site context. A consolidated matrix is provided in Annex C.2 to explain how each selection parameter can be interpreted by climate, what evidence should be collected, and which cautions should be considered before shortlisting crops.

Final Selection and Validation: The scoring outcome should be combined with qualitative site validation before a final crop decision is made. The following four categories can be used to communicate the level of confidence associated with each candidate crop:

- Recommended: strong score, strong local evidence and no major unresolved site constraints.
- Conditionally recommended: good score but requires clarification on one or more issues such as irrigation, machinery, market access or PV layout.
- Pilot testing candidate: promising but evidence is limited or performance under shade is uncertain.
- Not recommended: fails technical prerequisites or has major unresolved agronomic, operational or market risks.





4.3 Climate-Specific AgriPV System Design and Integration across climatic zones[61]

The site assessment and crop-selection process establish the physical, agricultural, and operational conditions that the AgriPV system must accommodate. The next step is therefore to translate these conditions into appropriate system configuration (shown for different climatic zone in Table 38, Table 39, Table 40, Table 41, Table 42). Because climatic conditions influence crop light requirements, water management, structural loads, material durability, access, and PV performance in different ways, AgriPV systems should be adapted to the climatic and agricultural context rather than based on a single standard configuration.[62]

61 Source: PwC analysis and stakeholder consultation

62 Disclaimer: The climate-specific design configurations detailed herein serve as a high-level conceptual framework for preliminary planning and are not a technical specification. This information is illustrative, not a performance guarantee, as the success of any AgriPV project is dictated by local conditions that supersede this general guidance. Therefore, all projects require detailed design by qualified structural and electrical engineers to ensure safety and code compliance. Likewise, all crop strategies must be validated by local agronomists, and potential benefits such as water savings or frost protection must be modelled for the specific site and should not be assumed.

Table 38: Key AgriPV system design considerations and the integration approach specific to the Arid Zone

Key Consideration	Revised Integration Approach
System design consideration	AgriPV design in arid regions should be structured around three objectives: reducing crop and soil heat stress, conserving scarce water, and maintaining enough PAR for crop growth. Winter crops such as wheat, gram or similar light-demanding crops may require wider inter-row spacing, lower panel density or seasonal tracking strategies to avoid excessive shading. • Ground clearance should be based on the tallest crops grown during the year, the height and working envelopes of tractors/harvesters, and safe movement of farm workers and O&M personnel. • Inter-row spacing should balance PV self-shading, crop light requirements and machinery passage. A moderate GCR may be suitable, but high panel density should be avoided unless crop shade tolerance is confirmed. • Layout should provide clear turning areas at row ends and avoid placing support columns in machinery travel paths, irrigation channels or natural drainage lines.
Solar infrastructure and module layout	Because arid sites usually have high solar irradiance, the design should not maximise PV density at the expense of crop productivity. Single-axis tracking can be useful where it allows seasonal control of shading while improving energy yield. Fixed-tilt systems may remain appropriate where cost simplicity and low maintenance are priorities. • Design should include anti-soiling provisions because dust accumulation can reduce PV performance and cleaning water may be limited. • Panel tilt and row orientation should consider seasonal sun paths, wind-blown dust, cleaning access and the need to avoid excessive shade on winter crops. • Module spacing should be adjusted to maintain airflow and avoid stagnant, overheated zones under the array.
Soil health and conservation management	Arid soils are often low in organic matter and may face salinity or crusting risks. AgriPV shading can reduce soil temperature and evaporation, but runoff from panels can create local erosion if not properly dispersed. • Soil-health measures should include compost or farmyard manure, mulching, reduced tillage and cover crops where water availability permits. • Where salinity is present, crop choice and irrigation scheduling should be aligned with soil electrical conductivity and irrigation-water quality. • Panel runoff should be spread, harvested or routed carefully so that it does not concentrate erosion at panel drip lines.
Alignment with irrigation method	The AgriPV layout should be planned around existing irrigation systems rather than forcing irrigation infrastructure to adapt after installation. Before construction, wells, pumps, underground pipelines, filters, valves, field channels and outlets should be mapped. • Drip or subsurface drip irrigation is generally preferred because it improves water-use efficiency and reduces evaporative losses. • Support structures may be used to carry drip lines or monitor cables, but they should not obstruct farm operations. • Cable trenching and foundation works should avoid damaging buried irrigation pipelines or recharge structures.
Water-energy nexus	AgriPV systems in arid zones can become part of the water-management cycle. Shade may reduce evapotranspiration, meaning the combined water loss from soil evaporation and plant transpiration, while panel surfaces can be used for rainwater harvesting where rainfall events occur. • Gutters may channel panel runoff into storage ponds, recharge pits or tanks, provided overflow and sediment control are designed properly. • Soil-moisture sensors can help adjust irrigation timing and quantify actual water savings. • Water savings should be treated as indicative until validated by crop and field-level monitoring.

Table 38: (continued) Key AgriPV system design considerations and the integration approach specific to the Arid Zone

Key Consideration	Revised Integration Approach
Crop and operational compatibility	Crop selection should prioritise crops that benefit from moderate shade and water conservation, while avoiding over-shading of light-demanding crops. High-value vegetables, herbs and selected fruits may be considered where water and market access are reliable. • Crops should be screened for shade response, height, canopy spread, root depth, salinity tolerance and market value. • The system should remain compatible with sowing, harvesting, spraying, inter-cultural operations and crop residue management. • Crops should not be recommended solely because they are suitable for an arid climate; field-level water and soil conditions remain decisive.
Limitations / disclaimers	AgriPV benefits in arid zones are highly dependent on crop type, shade level and irrigation method. Excessive shade can reduce yields of light-demanding crops even if it improves soil moisture. • Salinity, groundwater availability and irrigation-water quality must be assessed before recommending crops or system design. • Rainwater harvesting potential depends on actual rainfall frequency, storage capacity and water quality. • Dust soiling and cleaning-water requirements should be considered in both the design and O&M plan.

Table 39: Key AgriPV system design considerations and the integration approach specific to the Semi-Arid Zone

Key Consideration	Revised Integration Approach
System design consideration	Semi-arid AgriPV design should support resilience against variable rainfall, dry spells, high wind exposure and mixed crop-livestock systems. The system should be designed not only as a power plant, but also as a moisture-conservation, erosion-control and livelihood-stabilisation structure. • Ground clearance should support crop operations and, where relevant, safe movement of sheep, goats or cattle. • Panel density should reduce heat and evaporation while allowing enough rainfall to reach crops and pasture. • Layout should follow farm contours where possible and avoid creating runoff channels that increase erosion.
Solar infrastructure and module layout	Fixed-tilt systems may be appropriate where simplicity and cost control are important, while single-axis tracking may be considered where additional energy revenue and seasonal light control justify the cost. • Spacing should allow access for small and medium farm equipment, grazing paths and maintenance vehicles. • Structures should be designed to resist wind loading and reduce near-ground wind speed where erosion is a concern. • Cable routes should be protected where livestock integration is proposed.
Water and soil resource management	The main design objective is to maximise the value of scarce and unpredictable rainfall. During dry periods, shading can conserve residual soil moisture. During intense rainfall, panels can reduce raindrop impact but may concentrate runoff if not designed carefully. • Gutter systems, channels, swales or farm ponds can capture and store panel runoff for supplemental irrigation. • Soil cover, mulching, cover crops and conservation tillage should be integrated to reduce evaporation and erosion. • Runoff should be slowed and infiltrated where possible rather than discharged rapidly from the site.

Table 39: (continued) Key AgriPV system design considerations and the integration approach specific to the Semi-Arid Zone

Key Consideration	Revised Integration Approach
Integration with farming and livestock systems	Semi-arid AgriPV is particularly relevant for agro-pastoral systems, where crops and livestock operate together. The panel shade can improve animal comfort and forage persistence, especially during hot periods. • Livestock areas should include protected wiring, non-toxic materials, fencing, water points and sufficient shade distribution. • Stocking rates should be managed so animals do not compact soil, damage vegetation or disturb foundations. • If forage production is planned, crop selection should include shade-tolerant grass, legumes or mixed pasture species suited to local rainfall.
Supplemental irrigation strategy	AgriPV systems can enable limited but strategic irrigation during dry spells. Captured rainwater may be used for supplemental irrigation during critical crop growth stages at critical crop growth stages rather than full-season irrigation. Drip irrigation can be used for high-value crops in selected rows or zones. Irrigation design should be modular, allowing farmers to prioritise higher-value crops when water is limited. Soil-moisture monitoring is useful for deciding when supplemental irrigation is needed. • Drip irrigation can be used for high-value crops in selected rows or zones. • Irrigation design should be modular, allowing farmers to prioritise higher-value crops when water is limited. • Soil-moisture monitoring is useful for deciding when supplemental irrigation is needed.
Crop and operational compatibility	Crop systems may include drought-tolerant cereals and pulses, forage crops, vegetables under supplemental irrigation and intercropping systems. Crop choice should reflect whether the farm is primarily rain-fed, irrigated, livestock-based or mixed. • Shade-sensitive crops should be placed in higher-light zones between panel rows. • Forage systems need sufficient light and grazing management to avoid overuse under panels. • Farm access should be maintained for sowing, harvesting, fodder collection and animal movement.
Limitations / disclaimers	Semi-arid AgriPV benefits depend strongly on rainfall timing, storage capacity and farm management. A system that works well for supplemental irrigation may not be sufficient for full irrigation demand. • Livestock integration requires additional electrical safety, fencing and animal-welfare planning. • Water-harvesting benefits should not be assumed without rainfall-runoff modelling and storage design. • Overgrazing can reduce vegetation cover and increase erosion if not managed.



Table 40: Key AgriPV system design considerations and the integration approach specific to the Tropical Zone

Key Consideration	Revised Integration Approach
System design consideration	Tropical AgriPV systems must balance solar protection with rainfall, humidity, disease pressure and year-round farming activity. In many tropical areas, the key risk is not water scarcity but excess water, poor drainage, fungal disease and corrosion. • Ground clearance should be higher where airflow, manual access, tall crops or small machinery movement are required. • Inter-row spacing should maintain sufficient PAR while improving ventilation and reducing humidity accumulation. • Layout should support frequent access for weeding, pruning, pest management, harvesting and drainage maintenance.
Solar infrastructure and structural durability	Tropical structures should be designed for high humidity, heavy rainfall and, where applicable, cyclonic or storm winds. Material durability is a key determinant of project life. • Use corrosion-resistant materials such as hot-dip galvanized steel, aluminum or appropriate coated components. • Electrical connectors, junction boxes and cable routes should have strong water ingress protection. • Lightning protection and earthing should be considered in storm-prone regions. • Panel tilt should support drainage and self-cleaning while accounting for wind uplift.
Panel spacing, ventilation and disease control	Panel spacing should be designed not only for light but also for airflow. Reduced air movement under dense arrays can increase humidity and fungal disease risk. • Rows should be oriented with prevailing winds where it is feasible to improve natural ventilation. • Crop spacing, pruning and canopy management may be needed under panels to reduce disease pressure. • A more open layout may be preferable for dense-canopy crops or humid sites even if it reduces PV density.
Rainfall and runoff management	Heavy tropical rainfall can cause erosion, compaction, nutrient leaching and waterlogging. AgriPV panels can reduce direct raindrop impact, but concentrated runoff from panel edges must be managed carefully. • Drainage channels, infiltration trenches, grassed waterways or recharge pits should be incorporated at the design stage. • Panel runoff may be harvested, but overflow pathways must be designed to avoid erosion and flooding. • Foundations should be designed considering saturated soils and water exposure.
Pest, disease and weed management	Tropical AgriPV design should make integrated pest management practical. IPM refers to combining monitoring, biological, cultural and chemical measures to control pests with minimum unnecessary chemical use. • Sufficient worker access should be provided for crop scouting, fungicide application, harvesting and pruning. • Structures can support pheromone traps, sticky traps or sensors where appropriate. • Partial shade may suppress some sun-loving weeds, but humid shaded zones may favour other pests or diseases.



Table 40: (continued) Key AgriPV system design considerations and the integration approach specific to the Tropical Zone

Key Consideration	Revised Integration Approach
Crop and operational compatibility	Shade-adapted or partial-shade-tolerant crops such as coffee, cacao, vanilla, ginger, turmeric, leafy vegetables and selected horticultural crops may be suitable depending on local climate and market conditions. • Crop choice should consider disease resistance, canopy density, harvest frequency and drainage tolerance. • Continuous cropping systems require durable access paths and year-round maintenance planning. • AgriPV layout should not obstruct dense planting patterns or irrigation networks.
Limitations / disclaimers	Tropical AgriPV should not be assumed to produce universal water-saving benefits. In humid zones, drainage and disease control may be more important than water conservation. • Increased humidity under panels can increase fungal disease risk if airflow is inadequate. • Storm, lightning and corrosion risks and impacts from pesticides and fertilizer spray require site-specific engineering design. • Tropical guidance should be localized using rainfall intensity, wind speed, soil drainage and crop disease data.

Table 41: Key AgriPV system design considerations and the integration approach specific to the Temperate Zone

Key Consideration	Revised Integration Approach
System design consideration	Temperate AgriPV systems must balance crop sunlight needs, mechanised agriculture, seasonal weather protection and winter structural performance. The design should evaluate both annual energy yield and seasonal crop-light availability. • Ground clearance and row spacing should be determined by actual farm machinery dimensions, turning radii and crop operations. • Spring and autumn low sun angles should be modelled because these periods may be crop-sensitive and more prone to shading losses. • The layout should remain flexible enough to support crop rotations rather than only one crop type.
Solar infrastructure and light management	Fixed-tilt systems may be simpler and cheaper, while trackers and bifacial systems can improve seasonal light and energy management. Bifacial modules generate power from both sides, using reflected light from the ground or snow. • Single-axis trackers may help reduce excessive shade during sensitive crop stages. • Bifacial modules may be helpful where ground reflectivity is high, or snow cover is common. • Panel pitch should be designed using crop-light modelling, not only PV yield optimisation.
Weather protection and season extension	In temperate zones, AgriPV value often comes from protection as much as water saving. Panels can reduce exposure to hail, intense rain, sunscald and some frost events. • For high-value crops, hail and heavy-rain protection can reduce physical crop damage. • Panel canopy may slightly reduce frost risk in some conditions by moderating radiative heat loss, but this benefit is not guaranteed. • Stormwater and snowmelt runoff should be managed to prevent erosion or waterlogging.



Table 41: (continued) Key AgriPV system design considerations and the integration approach specific to the Temperate Zone

Key Consideration	Revised Integration Approach
Integration with mechanised farming	Temperate agriculture is often highly mechanised, so AgriPV adoption depends on co-design with farm operations. • Column placement should avoid machinery routes, sprayer paths, loading areas and headlands. • Row spacing should reflect the widest operational equipment likely to be used, not only current crop operations. • Where large machinery cannot be accommodated, the report should clearly state whether smaller equipment or different crops are assumed.
Soil, water and biodiversity management	AgriPV systems may reduce evaporative losses during summer drought periods and reduce erosion during intense rainfall. They can also support groundcovers, pollinator strips or biodiversity corridors where compatible with crop production. • Soil-moisture monitoring can support better irrigation timing for high-value crops. • Cover crops or living mulches may reduce erosion and improve soil structure. • Biodiversity plantings should not obstruct crop operations or increase pest pressure.
Crop and operational compatibility	Potentially suitable crop groups include berries, leafy greens, brassicas, herbs, asparagus, grapes and other high-value horticultural crops. Suitability depends on local light, disease and market conditions. • Rotational crops should be checked separately because a layout suitable for leafy greens may not support sun-loving grains. • Crop calendars should be aligned with seasonal shade patterns. • Farm operators should validate whether AgriPV structures affect spraying, harvesting and logistics.
Limitations / disclaimers	Temperate AgriPV benefits depend on seasonal light conditions and cannot be judged only from annual solar yield. • Frost protection benefits are variable and should not be guaranteed without local evidence. • Snow load, hail load and winter maintenance should be reviewed by qualified structural engineers. • Crop rotation flexibility should be considered before locking the layout around one crop.



Table 42: Key AgriPV system design considerations and the integration approach specific to the Continental Zone

Key Consideration	Revised Integration Approach for Report Use
System design consideration	Continental AgriPV systems operate under large seasonal temperature swings, short growing seasons, frost, snow, hail, wind erosion and freeze-thaw cycles. The design should be both structurally robust and seasonally adaptive. • Ground clearance should account for crop height, large machinery, snow accumulation and maintenance access. • Row spacing should allow early-season sunlight penetration and machinery movement. • The AgriPV design should be linked to crop calendar stages, not just annual PV generation.
Dynamic light management	Single-axis trackers can be valuable where they allow seasonal control of shading. During early spring, trackers may be positioned to maximise low-angle sunlight for winter annual or early crops. During summer, they can provide protective shade for heat-sensitive crops. • Tracker stow positions should include wind safety and snow-shedding modes. • Control logic should be coordinated with crop growth stages where feasible. • Dynamic systems improve flexibility but add moving parts, maintenance and cost.
Snow, frost and foundation design	Structures should be designed for snow loads, frost heave and freeze-thaw impacts. Frost heave occurs when freezing soil expands and can lift or distort foundations. • Foundations should extend below local frost depth where required. • Module tilt or tracker angle should support snow shedding. • Cold-rated cables, connectors and moving parts should be selected where freezing temperatures are expected. • Access routes for winter maintenance should be identified early.
Bifacial technology and snow albedo	Bifacial panels can be beneficial in continental climates because snow has high albedo, meaning it reflects a large share of sunlight. Reflected light can increase backside generation when snow cover is present. • Bifacial gain should be modelled using local snow-cover duration and ground reflectivity. • Elevated designs may improve rear-side light capture but can increase structural cost. • Benefits are strongest where snow cover is frequent and panels remain clear enough to generate power.
Season extension and weather protection	AgriPV systems can provide partial protection from hail, storm events and some frost exposure, enabling diversification into higher-value crops in regions otherwise dominated by commodity grains. • High-value crops may benefit from reduced hail damage and improved microclimate stability. • Short-season crops should be selected with crop calendar and shade timing in mind. • Weather protection should be evaluated against additional structural cost.

Table 42: (continued) Key AgriPV system design considerations and the integration approach specific to the Continental Zone

Key Consideration	Revised Integration Approach for Report Use
Integration with farming systems	Continental farming often uses large machinery and wide fields. AgriPV layouts must either accommodate this equipment or clearly assume a transition to smaller-scale, high-value farming systems. • Conservation of tillage and cover crops can complement AgriPV by reducing erosion and conserving moisture. • Shade-tolerant cover crops such as selected clovers, vetch or rye may be used where locally appropriate. • Windbreak effects from panels may reduce topsoil loss but should be validated for site exposure and layout.
Limitations / disclaimers	Continental AgriPV requires detailed structural and seasonal analysis. Snow, frost and freeze-thaw effects can materially affect cost and reliability. • Tracker systems can improve seasonal flexibility but require additional O&M planning. • Bifacial snow-albedo gains should be modelled locally and not assumed universally. • Crop benefits depend on precise alignment between crop calendar, sun angle, snow season and PV operating strategy.

Cross-Zone Design Summary Matrix

The five climate-zone assessments demonstrate that the relative importance of AgriPV design parameters changes with climatic and agricultural context. The following matrix consolidates these differences into a comparative reference, highlighting the dominant risks, panel-spacing considerations, water-management priorities, and structural requirements for preliminary planning presented in Table 43.

Table 43: Summary of five agro-climatic zones and a brief of the AgriPV design considerations

Design variable	Arid	Semi-Arid	Tropical	Temperate	Continental
Dominant design risk	Heat, water scarcity, salinity, dust	Variable rainfall, erosion, livestock integration	Humidity, rain, disease, corrosion, storm risk	Seasonal light, frost, hail, mechanisation	Snow, frost, short growing season, large machinery
Panel spacing logic	Moderate to wide; protect PAR for light-demanding crops	Moderate to wide; allow rainfall and grazing/crop access	Wide enough for airflow and drainage	Machinery and low-sun access driven	Wide or dynamic for seasonal light and machinery
Preferred water strategy	Drip/subsurface drip, runoff capture, salinity management	Rainwater harvesting, supplemental irrigation, soil cover	Drainage, controlled runoff, infiltration trenches	Soil-moisture monitoring and supplemental irrigation	Snowmelt/rainwater storage and drought buffering
Key structural priority	Clearance, dust management, irrigation protection	Livestock-safe wiring, wind/erosion resilience	Corrosion, wind uplift, lightning and drainage	Snow/hail load and machinery clearance	Snow load, frost-depth foundations and tracker stow

Taken together, the assessment approach presented in this chapter establishes a climate-responsive pathway for AgriPV planning, moving from site suitability and crop selection to system configuration, operation and maintenance, and environmental and project risks. The analysis across the five climatic zones demonstrates that AgriPV design cannot be based on a single configuration or set of parameters. Instead, the appropriate balance between agricultural productivity, solar generation, water and resource management, structural performance, farm operations, and system reliability needs to be determined in relation to the specific climatic, agricultural, and site conditions. The climate-zone considerations presented in this chapter therefore provide a structured basis for preliminary planning and design, while detailed project-level engineering, agronomic validation, environmental assessment, regulatory review, and economic evaluation remain essential before implementation.

The design choices established at this stage also have direct implications for how an AgriPV system will be operated, maintained, and integrated with the electricity system. For example, system configuration, accessibility, mounting arrangements, agricultural activities, and PV capacity can influence O&M requirements, safety, asset management, and grid-interconnection considerations. Building on the climate-responsive design considerations developed in this chapter, the next chapter examines the key considerations for operation and maintenance and grid connectivity of AgriPV projects, with a focus on ensuring that the interaction between agricultural activities, PV assets, and the electricity grid is considered throughout the project lifecycle.

ILLUSTRATIVE AGRIPV SYMBIOTIC DESIGNING FOR SAMPLE SITES

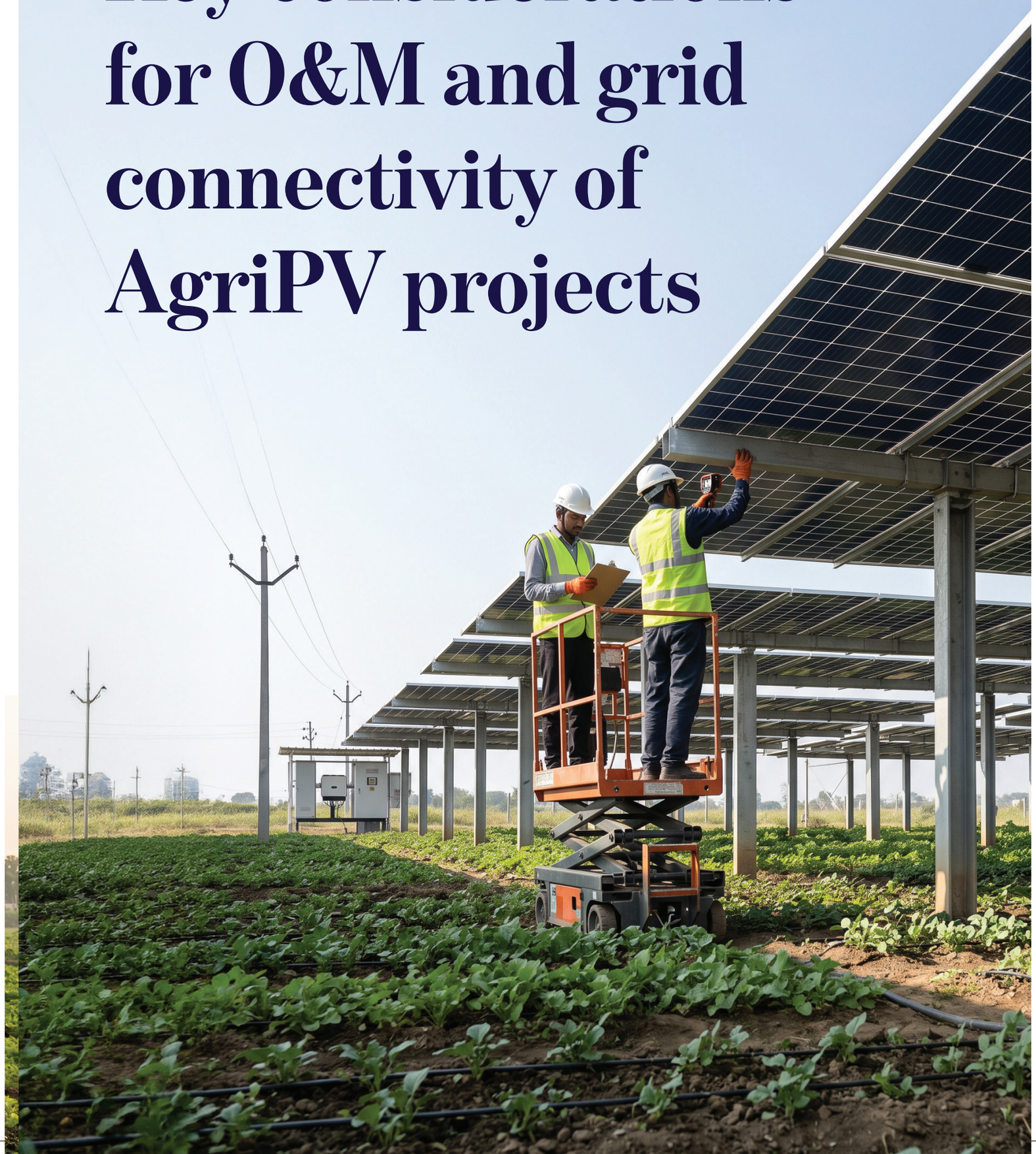
Appendix D presents brief case studies showing how the toolkit's crop selection framework is applied in practice across sample sites in five climatic zones: Arid (Minya, Egypt), Tropical (Telangana, India), Temperate (Himachal Pradesh, India), and Continental (Grafschaft, Germany).

For each site, the same process is followed: analyzing local climatic, agricultural, and economic conditions; adjusting the prioritization matrix to local needs; filtering and scoring suitable crops; and producing a ranked shortlist. The appendix also links crop choices to different AgriPV configurations—Elevated, Vertical, and Polyhouse—showing how design affects agricultural strategy. Overall, it turns the toolkit's methodology into practical, climate-specific examples.



CHAPTER 05

Key considerations for O&M and grid connectivity of AgriPV projects



5.1 O&M Comparison

This section outlines the key challenges observed during the operation of the AgriPV project, including agricultural challenges, PV system challenges, environmental challenges, and social challenges. Further, these challenges are analysed across different climatic zones.

Agricultural challenges for the operation of the AgriPV system

Though a typical AgriPV project provides a promising solution for sustainable land use, integration of the two systems introduces several challenges for crop production that can be carefully managed by appropriate design and management practices.

The most significant challenge is the reduction in Photosynthetically Active Radiation (PAR) reaching the crops. The solar panels cast shadows, and the extent and duration of this shading directly impact the light available for photosynthesis. This can lead to reduced plant growth, lower biomass accumulation, and potentially decreased crop yields if not appropriately managed. Another major challenge is the alteration of the microclimate. Panels change the temperature, humidity, and wind speed at the crop level. While this can be beneficial in some climates, it can be detrimental in others by, for instance, increasing the risk of fungal diseases due to higher humidity and reduced airflow.

Furthermore, the physical presence of the panel mounting structures creates physical obstruction, which can significantly hinder or complicate the use of standard agricultural machinery for activities like planting, tilling, pest control, and harvesting. This often necessitates investment in specialised or smaller equipment. Besides, there is the challenge of water distribution. Panels can intercept rainfall, leading to non-uniform soil moisture patterns where areas directly under the panels remain dry while the areas between rows receive excess water from runoff, if the drainage is not appropriately managed. This can create waterlogged and dry zones within the same field.

Variations by Climatic Zones: The nature and severity of these challenges vary significantly depending on the regional climate.

- **Arid and Semi-Arid Zones:** The primary challenge is to optimise light transmission for staple crops that still require significant sun exposure. However, the partial shading provided by the panels is highly advantageous, as it buffers crops from extreme heat and high solar radiation. This reduction in heat stress can lead to significantly improved water use efficiency, with studies showing water savings of 15-30%[63]. The shade reduces soil and canopy temperature, lowers crop water demand (evapotranspiration), and can result in higher yields for certain crops compared to open-field cultivation in the same climate.
- **Temperate Zones:** In temperate climates, the primary challenge is balancing the need for solar energy production with the seasonal light requirements of crops. During cool, overcast periods in the spring or autumn, the shading from panels can be a significant liability, delaying crop development and reducing yields of sun-loving crops. The design must be carefully optimised—using wider spacing or tracker systems—to maximise sunlight exposure during critical growing periods. The reduction in airflow can also increase the duration of leaf wetness after rain, elevating the risk of diseases like powdery mildew or late blight.
- **Tropical and Humid Zones:** In these regions, which are characterised by high temperatures, high humidity, and heavy rainfall, the main challenge shifts from light availability to disease management. The reduced airflow and increased humidity under the panels can create a perfect breeding ground for fungal and bacterial pathogens. Therefore, system design must prioritise ventilation, for example, by increasing the height of the panels or using a less dense panel arrangement. The interception of intense rainfall by the panels can be beneficial in preventing soil erosion and physical damage to delicate crops.

63 Raihan et al., Design of an Agro-photovoltaic system to find shade tolerant crops perspective to Bangladesh, Cleaner Energy Systems, Volume 10, 2025, https://doi.org/10.1016/j.cles.2025.100174

- **Continental Zones:** Characterised by hot summers, cold winters, and large seasonal temperature variations, continental zones present a dual challenge. During hot summers, the shading effect is beneficial, mitigating heat stress and reducing water requirements, like in arid zones. However, the primary challenge arises during the spring and fall. Shading can delay the thawing and warming of the soil in spring, shortening an already constrained growing season and stunting the early development of key crops like corn and soybeans.

The structural design also faces a significant challenge from heavy winter snowfall. The system must be engineered to withstand the considerable weight of accumulated snow (snow load), and panel tilt may need to be adjusted to help shed snow. Furthermore, rapid snowmelt can exacerbate the issue of uneven water distribution, leading to soil saturation in some areas and dry patches in others.

Variations by Crop Type: The suitability of a crop for an AgriPV system is largely determined by its light saturation point and growth habit.

- **Shade-tolerant Crops:** Leafy greens (lettuce, spinach, kale), many herbs (cilantro, chives, mint), and certain root vegetables (radishes, beets) are ideal candidates for AgriPV. These crops have low light saturation points and can thrive in partial shade. In fact, for these crops, the shade can be beneficial, leading to larger, more tender leaves and preventing bolting in hot weather. The challenges are minimal and mostly related to machinery access.
- **Sun-loving Fruiting Crops:** Crops such as corn, wheat, tomatoes[64], peppers, and most berries may show varying results depending on the shade level and heat stress. For example, an agriphotovoltaic greenhouse trials in Spain reported yield reductions of approximately 15% and 26% under 30% and 50% shading, respectively, compared with unshaded controls, although as per the study shading reduced heat stress and fruit sunscald and improved microclimatic conditions. Other studies also show yield gains in these crops in varying AgriPV configurations. As a general principle, sun-loving fruiting crops have high light requirements for flowering and fruit development. Significant shading may lead to yield losses, delayed ripening, and lower fruit quality (e.g., lower sugar content) in specific conditions. To successfully cultivate these crops, AgriPV designs must employ strategies to maximise light penetration, such as using fewer panels per acre, arranging them in a checkerboard pattern, or utilising sophisticated tracking systems that can adjust panel angles to prioritise crop light needs at specific times of the day or year.
- **Root and Tuber Crops:** For crops like potatoes and carrots, the challenge is two-fold. While they have moderate light requirements, the primary issue is the physical interference of support structures with mechanical soil cultivation and harvesting, which are essential for these crops. The design must ensure that row spacing and foundation placement allow for the passage of specialised diggers and other equipment without damaging the solar infrastructure or the crop.

PV system challenges for the operation of the AgriPV project

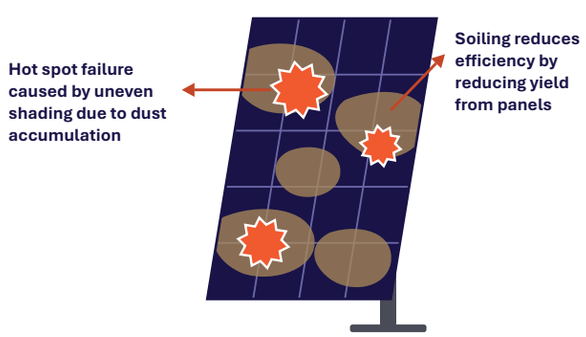
AgriPV systems face various technical and operational challenges that must be addressed to ensure their efficient performance. The following sections explore some of these issues in detail.

64 Kujawa, Anna, Julian Kornas, Natalie Hanrieder, Sergio González Rodríguez, Lyubomir Hristov, Álvaro Fernández Solas, Stefan Wilbert, Manuel Jesus Blanco, Leontina Berzosa Álvarez, Ana Martínez Gallardo, and et al. 2025. "Tomato Yield Under Different Shading Levels in an Agriphotovoltaic Greenhouse in Southern Spain" AgriEngineering 7, no. 6: 178. https://doi.org/10.3390/agriengineering7060178

Dust Accumulation and creation of hot spots

When dust, dirt, bird droppings or other debris collect on the solar panels (shown in Figure 32), it reduces the amount of sunlight that reaches the panels. This lowers the energy output. If dirt is unevenly spread, it can cause certain parts of the panels to heat up more than others, which may lead to hot-spot failures.

Figure 32: Creation of hot spots due to dust accumulation



Cleaning solar panels helps maintain their performance, but it must be done carefully to avoid damage. Cleaning can be done on a regular schedule or only when needed (called “condition-based” cleaning). Special sensors can detect how dirty the panels are and trigger cleaning. However, sometimes nature helps, like when heavy rain washes the panels clean. Light rain may not clean well and can even make things worse by sticking dust to the panels. It has been observed that dust in AgriPV system is comparatively lower than simple ground-mounted system[65].

Wiring and cabling issues

The following issues can occur in the cabling system:

- **UV exposure:** Sunlight degrades wire ties and insulation over time. This will be common in the case of wires which are exposed to open air, and they are more prone to damage.
- **Rub or shift of wire:** Wind or temperature changes can cause wires to rub or shift, leading to damage. And to manage this damage, there is a requirement for more frequent inspections and maintenance, adding to the costs of O&M.
- **Inappropriate tension:** Wires pulled too tight or pinched can deform and fail, and can add to additional maintenance costs
- **Animal damage:** Squirrels and other small animals like rats may chew wires, causing disruptions and the need for additional maintenance.
- **Over-bundling:** Large wire bundles trap heat, degrading insulation faster.

Transformer failure

In an AgriPV system, the failure of a transformer poses a significant operational challenge, potentially idling the entire plant for months. GSUs are not only costly and difficult to replace due to long lead times, but their size and weight also complicate logistics, often requiring cranes and special transport permits.

65 Acquilin Medonna, et.al. Harvesting sun amplified: A comprehensive review of agriphotovoltaics and floatovoltaics with a focus on India’s potential, Solar Compass, Volume 15, 2025, https://doi.org/10.1016/j.solcom.2025.100132



Impact of moisture on PV modules

Moisture is a critical stress factor for PV modules, as its infiltration can weaken the adhesive bonds between different layers of the module. This degradation often leads to delamination, which compromises the structural integrity and performance of the module. Additionally, moisture can cause the loss of surface passivation and deteriorate anti-reflection coatings, both of which are essential for maintaining high energy conversion efficiency. Metallization elements, such as conductive pathways, are also vulnerable to corrosion when exposed to moisture. In outdoor environments, moisture manifests in various forms, including humidity, dew, rain, snow, and ice, each contributing to the long-term wear and degradation of PV systems.

Ammonia stress in agricultural setups

Ammonia's reactive nature poses a serious threat to photovoltaic modules in an AgriPV system. It can degrade plastics, adhesives, and metals used in solar panels. For instance, ammonia can break down the polymer chains in back sheets, making them brittle and prone to cracking, which compromises insulation and weather protection. It also causes yellowing of the encapsulant.[66], reducing light transmission to the cells. Metal components like aluminium frames and copper contacts corrode more rapidly, increasing electrical resistance and failure risk. Additionally, ammonia weakens sealants in junction boxes and wiring, allowing moisture to enter and potentially cause short circuits. Research by Fraunhofer ISE shows that such exposure can lead to a 10–15% drop in power output within just a few years.

Power curtailment in systems without BESS

Power curtailment in an AgriPV system without BESS will occur when excess electricity generated during peak solar hours cannot be stored and must be reduced or shut off to prevent overloading the grid. This leads to a loss of potential energy production and revenue, especially during periods of high solar irradiance. Without BESS, the system lacks the flexibility to shift energy usage to non-peak hours, making it more vulnerable to grid constraints and limiting its overall efficiency. Curtailment can also impact the economic viability of the project, emphasising the importance of strategic grid integration and load management in system design.

Environmental challenges for the AgriPV project operation

Environmental challenges refer to issues stemming from environmental factors such as weather, variation, water scarcity, etc. This section discusses the environmental challenges typically encountered during the operation of AgriPV projects. The key environmental challenges for the AgriPV project operation are listed below:

Extreme Temperatures

Climate change has increased the intensity of extreme weather events, including extreme high temperatures, which reduce the efficiency of PV panels and stress crops, and extreme cold temperatures, which risk damage to both panels and plants. Arid and continental climates are particularly susceptible to extreme temperature fluctuations.

66 The encapsulant in a solar panel—usually made of transparent EVA—is a protective layer that surrounds the solar cells between the glass and backsheet. It shields the cells from moisture, dust, and mechanical stress while allowing sunlight to pass through efficiently. It also ensures electrical insulation and structural stability, helping maintain the panel's performance and durability over time.

Water Scarcity

Limited water availability in arid and semi-arid regions poses significant challenges for irrigation and crop growth. Furthermore, dust and soiling of PV panels in water-scarce environments can reduce energy generation.

High Humidity and Precipitation

Tropical climates experience high humidity and rainfall, which can lead to corrosion of PV system components and fungal diseases in crops. Heavy rainfall can also cause soil erosion and waterlogging, impacting crop yields.

Wind and Hail

Strong winds and hailstorms can damage PV panels and crops in all climatic zones, particularly in exposed locations. Temperate and continental climates often experience strong wind events.

Pests and Diseases

The microclimate created by the PV panels can influence pests and disease prevalence in crops. Specific pest and disease pressures vary depending on the climate and the crops being cultivated.

Table 44 summarizes the impact of environmental challenges according to varying climatic zones.

Table 44: Impact of environmental challenges according to varying climatic zones.

Climatic Zone	Impact of environmental challenges	
	Solar PV operation	Agricultural activities
Arid and Semi-Arid	High temperatures can reduce PV panel efficiency, while dust and sand deposition can further hinder energy capture. Water scarcity limits cleaning options, exacerbating the issue. Furthermore, intense solar radiation can accelerate material degradation, shortening the lifespan of PV components.	Water availability is the primary constraint for agriculture in these regions. AgriPV systems can exacerbate water stress by intercepting rainfall and increasing evapotranspiration rates in the immediate vicinity of the panels. Soil salinity can also be a concern, particularly with inappropriate irrigation practices. Selecting drought-tolerant crops and implementing efficient water management strategies are crucial for successful AgriPV implementation in these climates.
Tropical	High humidity and rainfall can accelerate corrosion and module degradation. Frequent and heavy rainfall can also increase soiling and necessitate more frequent cleaning. Furthermore, the risk of vegetation overgrowth around PV installations is significantly higher, requiring regular maintenance.	High humidity and temperatures can promote the spread of pests and diseases, impacting crop yields. Heavy rainfall can lead to soil erosion and nutrient leaching, further affecting agricultural productivity. Shade provided by PV panels can be beneficial in reducing heat stress on crops, but it needs careful management to avoid hindering photosynthesis.
Temperate	Snow and ice accumulation on PV panels during the winter months can significantly reduce energy generation. Seasonal variations in sunlight intensity also influence overall energy output. Appropriate panel angling and snow removal strategies are essential for optimising performance.	Managing shade patterns from PV panels throughout the growing season is crucial to ensure adequate sunlight for crops. Seasonal variations in temperature and precipitation require adaptable farming practices and crop selection.
Continental	Like temperate climates, snow and ice accumulation can reduce PV efficiency during winter. Extreme cold temperatures can also affect the performance of PV components. Furthermore, large temperature fluctuations can accelerate material degradation over time.	The short growing season in continental climates requires careful crop selection and management. AgriPV systems can provide some protection from extreme temperatures but must be designed to avoid excessive shading during the limited growing period.

Social Challenges

The social challenges associated with AgriPV operations are distinct from ground-mounted solar PV projects as they occur at the complex intersection of energy production, agriculture, and rural community life. Key issues include securing farmer acceptance, navigating concerns over loss of autonomy, and ensuring the equitable distribution of economic benefits. The social challenges have been explained as follows:

Farmer acceptance and autonomy

A primary social barrier is the potential resistance from farmers and landowners who may be sceptical of the AgriPV long-term effects on crop yields, soil health, and water resources. There is a significant concern that leasing land for AgriPV cedes operational control to an energy developer, thereby diminishing the farmer's autonomy over their own agricultural practices. This perceived loss of control and disruption to traditional farming methods can lead to a reluctance to adopt AgriPV systems.

Equitable Access and Benefit Distribution

There is a considerable risk that the financial and operational complexities of AgriPV will favour large, well-capitalized agricultural corporations over small-scale or family farms. This can exacerbate existing inequalities within the agricultural sector. Furthermore, conflicts can arise if the economic benefits from electricity generation and agricultural sales are not perceived as being distributed fairly among the energy developer, the landowner, the tenant farmer, and the wider local community.

Knowledge and Skill Gaps

AgriPV demands a hybrid skillset that combines agricultural science with the technical expertise required to operate and maintain solar energy infrastructure. Rural communities and local farm labourers may lack the necessary training to fill these new roles, leading to a reliance on an external workforce. This can create a sense of exclusion and limit the direct economic opportunities for the local population, hindering community buy-in and long-term project support.

Land-Use and Operational Management Conflicts

During the operational phase, conflicts can emerge between the needs of agricultural activity and solar energy generation. Disagreements may arise over issues such as the timing of panel cleaning, access for farm machinery, adjustments to panel tilting to optimise sunlight for crops, and responsibilities for site maintenance. Without clear governance and communication protocols, these operational frictions can strain the relationship between the farmer and the project operator.

Complexity of Economic and Lease Agreements

The legal and financial agreements underpinning AgriPV projects are inherently complex, involving long-term leases, revenue-sharing models, and clauses on liability for both crop performance and energy equipment. This complexity can be intimidating for landowners and farmers, creating an imbalance of power during negotiations with experienced energy developers. A lack of transparency or understanding of these agreements can foster mistrust and become a source of future disputes.



5.2 Assessment of the risk level of key challenges

To systematically evaluate the challenges, a risk-based approach was adopted. These challenges were identified through a combination of secondary research—drawing on NREL reports on O&M best practices and IEA PVPS studies on maintenance practices across different climates—and primary insights gathered from stakeholder consultations. Each potential challenge was assessed using two key criteria:

- **Probability of Occurrence –** categorized as High, Medium, or Low, based on the likelihood of the event happening. The probability of occurrence has been estimated based on the secondary research from well-known reports of NREL and IEA PVPS and through primary stakeholder consultations.
- **Impact Severity –** measured separately for its effect on power generation and crop production, also classified as High, Medium, or Low. The impact of occurrence is based on the secondary research from well-known reports of NREL and IEA PVPS and through primary stakeholder consultations.

By combining these two dimensions, a risk profile was created for each challenge. The results were then mapped in a tabular format, enabling clear visualisation of risks across both sectors. This approach helps in identifying high-priority challenges that pose significant risks and require immediate attention, as well as those with lower risk levels that may need monitoring rather than urgent intervention.

Based on probability

The operational challenges identified for AgriPV projects have been assessed for their likelihood of occurrence (Table 45) across different climatic zones—Semi-Arid, Arid, Tropical, Temperate, and Continental. This classification helps in understanding which challenges are more probable in specific environments.

Table 45: Mapping of operational challenges based on likelihood of occurrence in different climatic zones

Operational Challenge	Semi-Arid	Arid	Tropical	Temperate	Continental
Dust accumulation	High	High	Medium	Medium	Medium
Data connectivity	Medium	Medium	Medium	Medium	Medium
Transformer failure	Medium	Medium	Low	Low	Low
Corrosive environment	Medium	Low	High	Low	Low
Power Curtailment	Low	Low	Low	Low	Low
Extreme temperatures	Medium	High	Low	Medium	High
Reduced Light Availability	Low	Low	Medium	High	High
Uneven Water Distribution	Low	Low	High	Medium	High
Water Quality	Medium	Medium	Low	Low	Low
High Humidity & Precipitation	Medium	Low	High	Low	Low
Wind and hail	Medium	Low	Low	Medium	High
Icing and snowing	Low	Low	Low	Medium	High
Uneven Terrain	Low	Low	Medium	High	High
Limitation in machinery access	Medium	Medium	Medium	Medium	Medium
Pests and Diseases	Medium	Low	High	Medium	Low
Lack of skilled labor	Medium	Medium	Medium	Medium	Medium

From the analysis:

- **Dust accumulation** has a high probability in Semi-Arid and Arid zones, making it a major concern in dry climates.
- **Extreme temperatures** are highly probable in Arid zones, while high humidity and precipitation are more likely in Tropical regions.
- Challenges such as **transformer failure**, corrosive environment, and wind/hail events generally show **low to medium probability**, varying by zone.
- **Power curtailment and lack of skilled labour** have relatively lower probabilities overall.
- **Uneven water distribution is highly probable** in temperate, continental zones due to the rapid melting of accumulated snowfall

Based on impact

Each challenge has also been evaluated for its impact on power generation and crop production if it occurs (Table 46). This impact assessment is crucial because even challenges with low probability can have severe consequences, requiring contingency planning.

Table 46: Mapping of operational challenges based on impact in different climatic zones

Operational Challenge	Semi-Arid	Arid	Tropical	Temperate	Continental
Dust accumulation	Medium	Medium	Low	Low	Low
Data connectivity	Low	Low	Low	Low	Low
Transformer failure	High	High	High	High	High
Corrosive environment	Low	Low	Low	Low	Low
Power Curtailment	Medium	Medium	Medium	Medium	Medium
Extreme temperatures	Medium	High	Low	Medium	High
Reduced Light Distribution	Medium	Medium	Medium	High	High
Uneven Water Distribution	Low	Low	High	Medium	Medium
Water Quality	Medium	Medium	Low	Low	Low
High Humidity & Precipitation	Medium	Low	High	High	High
Limitation in machinery access	Medium	Medium	Medium	Medium	Medium
Wind and hail	Low	Low	Low	Low	Low
Icing and snowing	Low	Low	Low	Medium	High
Uneven terrain	Low	Low	Medium	High	High
Pests and Diseases	Medium	Low	High	Medium	High
Lack of skilled labor	Low	Low	Low	Low	Low

From the analysis:

- **Transformer failure** poses a high impact across all zones, making it a critical risk despite a lower probability in some climates.
- **Extreme temperatures and dust accumulation** have medium to high impacts, especially in Semi-Arid and Arid zones.
- Other challenges, such as **water quality, wind and hail**, generally have low to medium **impacts**, but their cumulative effect can still influence system performance.

Risk level

Both probability of occurrence and impact on power generation and crop production were evaluated across five climatic zones, Semi-Arid, Arid, Tropical, Temperate, and Continental, using a three-level scale (**High, Medium, Low**). The probability and impact were converted to numeric scores (**Low = 1, Medium = 2, High = 3**) and an overall risk score was computed by multiplying probability and impact ratings, and then classified as:

- **High Risk: Score 7–9**
- **Medium Risk: Score 4–6**
- **Low Risk: Score 1–3**

The combined risk matrix (shown in Table 47) for AgriPV challenges has been developed by ranking each challenge based on its probability of occurrence and impact severity

The following table is illustrative, presenting the identified challenges and their corresponding risk rankings based on the earlier probability and impact assessment. These risks have been evaluated on a generalized basis across five climatic zones. It is important to recognize that the analysis may vary significantly between geographies, zones, and even localities. Each site carries its own unique set of risks, which can only be accurately determined through a comprehensive feasibility study conducted for that specific location.

Table 47: Operational Risk Mapping across different climatic zones

Operational Risk	Semi-Arid		Arid		Tropical		Temperate		Continental	
	P*I	Ranking	P*I	Ranking	P*I	Ranking	P*I	Ranking	P*I	Ranking
Dust accumulation	3*2	Medium	3*2	Medium	2*1	Low	2*1	Low	2*1	Low
Data connectivity	2*1	Low	2*1	Low	2*1	Low	2*1	Low	2*1	Low
Transformer failure	2*3	Medium	2*3	Medium	1*3	Low	1*3	Low	1*3	Low
Corrosive environment	2*1	Low	1*1	Low	3*1	Low	1*1	Low	1*1	Low
Power Curtailment	1*2	Low	1*2	Low	1*2	Low	1*2	Low	1*2	Low
Extreme temperatures	2*2	Medium	3*3	High	1*1	Low	2*2	Medium	3*3	High
Water Quality	2*2	Medium	2*2	Medium	1*1	Low	1*1	Low	1*1	Low
Reduced Light Distribution	1*2	Low	1*2	Low	2*2	Medium	3*3	High	3*3	High
Uneven Water Distribution	1*1	Low	1*1	Low	3*3	High	2*2	Medium	3*2	Medium
Limitation in machinery access	2*2	Medium	2*2	Medium	2*2	Medium	2*2	Medium	2*2	Medium

Table 47: (continued) Operational Risk Mapping across different climatic zones

Operational Risk	Semi-Arid		Arid		Tropical		Temperate		Continental	
	P*I	Ranking	P*I	Ranking	P*I	Ranking	P*I	Ranking	P*I	Ranking
High Humidity & Precipitation	2*2	Medium	1*1	Low	3*3	High	1*3	Low	1*3	Low
Wind and hail	2*1	Low	1*1	Low	1*1	Low	2*1	Low	3*1	Low
Icing and Snowing	1*1	Low	1*1	Low	1*1	Low	2*2	Medium	3*3	High
Uneven Terrain	1*1	Low	1*1	Low	2*2	Medium	3*3	High	3*3	High
Pests and Diseases	2*2	Medium	1*1	Low	3*3	High	2*1	Low	1*3	Low
Lack of skilled labour	2*1	Low	2*1	Low	2*1	Low	2*1	Low	2*1	Low

Mitigation Plan for Challenges

The operational challenges, associated risks, and mitigation measures for AgriPV systems can vary significantly depending on local climatic conditions, agricultural practices, crop types, terrain characteristics, and project design configurations. For example, wind loading is a key concern in tropical and coastal regions, while snow loading and frost-related impacts are more relevant in continental climates. Consequently, mitigation strategies should be adapted to site-specific conditions and project requirements. Detailed mitigation measures across different risk categories are provided in Appendix C.1.



5.3 Grid Connectivity & Distributed Deployment Models

AgriPV Grid connectivity is a key determinant of AgriPV as it enables export of surplus electricity thereby providing a visibility around revenue from sale of such electricity to third parties such as Discom or industrial/ commercial consumers. While utility-scale AgriPV projects are primarily designed to export electricity to the grid, distributed and behind-the-meter (BTM) systems prioritize direct consumption of electricity for agricultural operations such as irrigation pumping, cold storage, pack houses, dairy facilities, and on-farm processing.

These deployment pathways (Table 48) present different opportunities and constraints, particularly in regions where grid infrastructure is weak, interconnection capacity is constrained, or project developers face lengthy connection approval processes. Such considerations are particularly relevant across several ISA member countries where rural network limitations can significantly influence project economics and deployment strategies.

5.3.1 AgriPV Deployment Models

Table 48: Comparison of AgriPV Deployment Models

Parameter	Distributed / Behind-the-Meter AgriPV	Utility-Scale Grid-Connected AgriPV
Primary objective	Energy cost savings, energy security, productive use of energy	Sale of electricity to utilities or power markets
Typical end-use	Irrigation pumps, cold storage, agro-processing, dairy operations, rural enterprises	Utility procurement, PPAs, merchant sale of power
Typical capacity range	kW to low-MW scale	Multi-MW to utility-scale installations
Grid dependency	Low to moderate	High
Exposure to interconnection delays	Limited	Significant
Revenue model	Reduced electricity expenditure and fuel savings	Electricity sales through PPAs or regulated tariffs
Primary stakeholders	Farmers, cooperatives, FPOs, agribusinesses	IPPs, utilities, infrastructure investors
Key design priority	Matching generation with agricultural load profile	Maximizing generation and export capacity

Utility-Scale Grid-Connected AgriPV

Utility-scale AgriPV systems are typically developed with the primary objective of exporting electricity to the grid. These projects benefit from economies of scale and can contribute significantly to national renewable energy targets; however, they are highly dependent on transmission and distribution infrastructure availability. Project development timelines may be influenced by substation capacity, network reinforcement requirements, grid-connection approvals, and curtailment risks, all of which can affect bankability and project returns.

Consequently, utility-scale AgriPV developments require site-selection criteria that extend beyond solar resource and agricultural suitability to include proximity to substations, available grid capacity, and expected interconnection timelines. In markets experiencing renewable energy connection backlogs, these factors can become critical project-development considerations.

Distributed and Behind-the-Meter AgriPV

Distributed AgriPV systems are designed to serve local energy demand directly, reducing dependence on grid infrastructure and minimizing exposure to transmission constraints. Such systems are particularly well suited for irrigation pumping, cold storage facilities, milk chilling centres, food processing units, and other productive agricultural loads that coincide with daytime solar generation profiles. By consuming electricity on-site, projects can derive value through avoided electricity purchases and reduced diesel consumption, rather than relying exclusively on energy exports.

For example, a horticulture farm may integrate an AgriPV installation with irrigation pumps and cold storage infrastructure, allowing solar generation to support both crop cultivation and post-harvest operations. In such configurations, project economics are driven largely by operational cost savings and improved energy reliability, making them less vulnerable to interconnection constraints and network upgrade requirements.



Financing and Policy Implications

The financing approach differs considerably between the two deployment models. Distributed AgriPV systems are often financed by farmers, cooperatives, agribusinesses, or through asset-leasing and concessional financing mechanisms. Their business case is typically supported by reduced energy costs, improved agricultural productivity, and enhanced energy security. In contrast, utility-scale projects generally rely on project finance structures supported by long-term power purchase agreements (PPAs), utility procurement programs, or wholesale electricity market participation.

From a policy perspective, distributed AgriPV deployment is supported by measures such as net metering, net billing, agricultural solarization programs, and concessional financing, while utility-scale projects depend more heavily on grid planning, transmission investments, renewable energy procurement frameworks, and streamlined interconnection procedures.

Table 49: PM-KUSUM Scheme Components Supporting AgriPV Integration

Policy / Mechanism	Connectivity Model	Typical Capacity Range	Relevance for AgriPV	Key Implication
PM-KUSUM Component A	Grid-connected, decentralized generation connected to nearby substations	500 kW – 2 MW	Suitable for elevated AgriPV systems where farming activity continues beneath the PV array	Enables farmers/FPOs to earn revenue from electricity sales while retaining agricultural land use [mnre.gov.in], [pmkusum.mnre.gov.in]
PM-KUSUM Component B	Behind-the-meter / off-grid	Solar pumps up to agricultural load	Supports AgriPV linked with irrigation infrastructure	Reduces diesel and grid dependence for irrigation operations [mnre.gov.in], [pmkusum.mnre.gov.in]
PM-KUSUM Component C (Individual Pump Solarisation)	Grid-connected self-consumption with surplus export	Pump-linked systems	Allows agricultural consumers to offset energy use and export surplus power	Suitable for farms integrating AgriPV with irrigation demand [mnre.gov.in], [pmkusum.mnre.gov.in]
PM-KUSUM Component C (Feeder Solarisation)	Feeder-level distributed solar	Multi-MW scale depending on feeder demand	Creates opportunities for aggregation of agricultural loads and local generation	Reduces Discom subsidy burden and improves rural power supply reliability [pmkusum.mnre.gov.in], [mnre.gov.in]
State Net Metering / Net Billing Regulations	Behind-the-meter with grid export	Typically, kW to low MW scale (state-specific)	Supports on-farm consumption applications such as cold storage, pack houses and processing units	Improves project economics through self-consumption and surplus power export.



The PM-KUSUM framework (Table 49) illustrates how distributed and decentralized deployment models can reduce reliance on large transmission infrastructure while supporting rural income generation and agricultural energy access.

For many ISA member countries, distributed and behind-the-meter AgriPV systems may provide a more practical near-term deployment pathway than utility-scale projects, particularly in regions experiencing grid constraints or lengthy interconnection timelines. By aligning electricity generation with agricultural demand, these systems can improve farm-level energy security, reduce operating costs, and support rural development objectives. Utility-scale AgriPV projects remain important for large-scale renewable energy deployment, but their success is more closely linked to grid readiness, transmission capacity, and long-term infrastructure planning.

Chapter 5 established that the success of an AgriPV project depends not only on an appropriate technical design, but also on how effectively the system can be operated, maintained, and connected to the electricity network. Considerations such as coordinated agricultural and solar maintenance, equipment accessibility, safety, monitoring, grid availability, evacuation infrastructure, and compliance with applicable regulations directly influence the long-term performance of the project. These factors determine whether the system can consistently deliver the intended agricultural and energy outputs under actual operating conditions.

However, achieving operational readiness is only one part of developing a sustainable AgriPV project. Each design and operational decision discussed in Chapter 5 carries a financial implication. For example, elevated structures, wider row spacing, specialised maintenance equipment, additional safety measures, grid-extension requirements, and storage or monitoring systems may improve functionality and resilience, but they can also increase capital and operating costs. At the same time, reliable operation and suitable grid connectivity can improve energy generation, reduce downtime, protect agricultural productivity, and strengthen the predictability of project revenues.

The discussion therefore moves naturally from determining how an AgriPV project should function in practice to assessing whether it can remain commercially viable over its operating life. Chapter 6 builds on the technical and operational foundations established in the preceding chapters by examining the economics and financing of AgriPV projects. It considers the major cost components, financial assessment parameters, revenue streams, business and ownership models, and financing instruments that collectively shape project bankability. This transition connects operational feasibility with financial decision-making, enabling stakeholders to evaluate AgriPV projects as integrated agricultural, energy, and investment systems.



CHAPTER 06

Economics & Financing



The economic viability of AgriPV systems is governed by the dual-revenue nature of the land use, where energy yields and agricultural outputs must be optimized simultaneously. A comprehensive understanding of the financial dynamics is paramount for stakeholders, including farmers, developers, and policymakers, to make informed investment decisions and unlock the full potential of this innovative land-use model.

This section provides a detailed examination of the project econometrics and financial considerations essential for the planning, development, and operation of AgriPV systems. It delves into the primary cost structures, differentiating between the initial Capital Expenditure (CapEx) for system setup and the recurring Operational Expenditure (OpEx) for ongoing maintenance and activities. Furthermore, the chapter outlines the diverse and resilient revenue streams inherent to AgriPV, which include not only the sale of electricity and agricultural products but also ancillary benefits such as carbon credits and government incentives.

To assess the financial performance and investment attractiveness of these projects, the section explores key financial metrics. These include the Levelized Cost of Electricity (LCOE), Net Present Value (NPV), Internal Rate of Return (IRR), and the Land Equivalent Ratio (LER), a metric of particular importance to dual-use systems. The discussion extends to various funding and financing mechanisms, from traditional government support to innovative approaches like blended finance and green bonds. Finally, the section analyses a range of business and ownership models—from farmer-owned to developer-led and joint ventures—providing a framework for structuring projects to align with the objectives and risk appetites of different stakeholders.

6.1 CapEx / OpEx Categories & Cost Components

The financial viability of an AgriPV project is fundamentally dependent on a thorough assessment of its initial and ongoing costs. These costs are categorized into Capital Expenditure (CapEx) and Operational Expenditure (OpEx), explained as follows:

Capital Expenditure (CapEx)

CapEx comprises the upfront investment required to develop an AgriPV system. Costs vary by technology, design, and project scale, with elevated and polyhouse systems typically requiring higher investment than vertical AgriPV systems. Key CapEx components include:

- **Solar PV system:** This is the most significant cost component and includes PV modules, inverters, and mounting structures. The design of mounting systems for AgriPV is more complex and expensive than for conventional ground-mounted PV, as it must accommodate agricultural machinery and optimize light for crops. Significant premiums are associated with elevated mounting structures (often 3 to 5 meters high) to allow for farm machinery movement.
- **Balance of System (BOS):** This encompasses all other electrical components, such as wiring, transformers, and equipment for grid connection.
- **Installation and construction:** These are the costs associated with the physical installation of the PV system, including labour, machinery, and site preparation.
- **Land preparation:** Costs related to clearing, levelling, and preparing the land to accommodate both the solar infrastructure and agricultural activities.
- **Agricultural equipment:** The project may require investment in new or modified farming equipment compatible with the AgriPV system's design, such as specialized irrigation systems.
- **Infrastructure development:** This includes the cost of building access roads, fencing, water systems (troughs, tanks), and storage facilities for agricultural produce.
- **Soft costs:** These include expenses for planning, permitting, grid connection studies, legal fees, and obtaining necessary licenses to operate.

Operational Expenditure (OpEx)

OpEx refers to the recurring costs associated with the day-to-day running and maintenance of the AgriPV system. Effective management of OpEx is crucial for the long-term profitability of the project. Key OpEx components are:

- **Operations and Maintenance (O&M):** This includes regular maintenance of the solar panels (e.g., cleaning), electrical equipment, and agricultural infrastructure. It also covers vegetation management.
- **Labour:** Wages for farm workers engaged in agricultural activities and for technical staff responsible for maintaining the PV system.
- **Lease payments:** In business models where the developer leases land from farmers, this is a significant and regular operating cost for the developer.
- **Insurance:** Premiums to cover potential risks such as damage to the PV equipment, crop failure, and public liability.
- **Administrative and miscellaneous costs:** These include expenses for managing lease agreements, compliance with regulations, monitoring, office supplies, and other ancillary costs.

The illustrative table comprising of typical project cost components for AgriPV project is provided in Table 50.

Table 50: Major cost components for an AgriPV project[67]

Illustrative

Capital Cost Component	Unit	Value
AgriPV Structure		
Solar Modules	USD Mn/MWdc	0.11 - 0.13
Elevated / Polyhouse / Vertical Mounting Structures	USD Mn/ tonne	0.0018 - 0.0025
Inverters	USD Mn/MW	0.025 - 0.040
DC Balance of Plant (Cables, SCB, Accessories)	USD Mn/MWdc	0.020 - 0.035
AC LV Cables	USD Mn/km	0.015 - 0.030
Illumination System, Earthing	USD Mn/MWdc	0.008 - 0.015
Erection Works	USD Mn/MWdc	0.025 - 0.045
Electrical Works (DC and AC)	USD Mn/MWdc	0.020 - 0.040
Civil Works	USD Mn	0.50 - 1.50
Surveys, Studies, Design & Engineering	USD Mn	0.20 - 0.50
Pooling Station		
Step-up / Step-down Transformers	USD Mn/MVA	0.020 - 0.050
Switchgear and Panels	USD Mn/MVA	0.010 - 0.030

67 Disclaimer: Indicative costs only; actual costs vary by project size, location, technology, and site conditions etc.

Table 50: (continued) Major cost components for an AgriPV project

Illustrative

Capital Cost Component	Unit	Value
SCADA, Surveillance, Fire Fighting, Safety and Monitoring	USD Mn	0.30 - 0.80
Buildings	USD Mn	0.15 - 0.50
Drains, Roads, Fencing and Gates	USD Mn	0.30 - 1.00
Grid Connection		
Overhead Line Towers (Single Circuit)	USD Mn/km	0.040 - 0.080
Bay at Substation (including protection systems)	USD Mn/MVA	0.015 - 0.040
Others		
Contingency	% of EPC Cost	3–5%
Local Area Development	USD Mn	0.05 - 0.30
Pre-Project Development Expenses (permits, approvals, etc)	USD Mn	0.10 - 0.50

The following table presents a consolidated overview of the typical cost considerations applicable to AgriPV project development across five major climatic zones.

The Table 51 is organized under four cost categories: (a) Design, (b) Construction, (c) Operations & Maintenance (O&M), and (d) Agriculture.

Table 51 Cost considerations for AgriPV projects across climatic zones

Cost Category	Arid	Semi-Arid	Tropical	Temperate	Continental
Design	Water-efficient layout, microclimate modelling and dust-aware spacing.	Optimise irradiance, crop light and irrigation under variable rainfall.	Prioritise drainage, cyclone resistance and crop-light management.	Design for snow, wind and seasonal light; consider hail/ rain protection.	Engineer for heavy snow, freeze–thaw cycles and snow-shedding tilt.
Construction	Remote logistics, difficult soils and wind/ dust protection increase civil and material costs.	Wind/hail-resistant structures and integrated irrigation infrastructure.	Drainage, soft-soil foundations and cyclone anchoring; monsoons may delay works.	Heavier foundations and supports for snow and wind loads.	Cold-rated materials and short winter construction windows raise costs.



Table 51 (continued) Cost considerations for AgriPV projects across climatic zones

Cost Category	Arid	Semi-Arid	Tropical	Temperate	Continental
O&M	Frequent dust cleaning and heat-related component replacement.	Periodic dust cleaning and added pest/disease control.	Intensive vegetation control and humidity-related electronics servicing.	Snow clearing plus crop-yield monitoring and compliance reporting.	Snow removal and inspections for thermal cycling and freeze–thaw damage.
Agriculture	Micro-irrigation and heat-/drought-resilient crops increase input costs.	Flexible irrigation, drought-tolerant crops and targeted replanting add costs.	Heat mitigation, airflow, disease control and rapid weed management.	Low-season light, fungal pressure and vegetation control affect recurring costs.	Short seasons, frost and summer irrigation constrain crops and increase advisory needs.





6.2 Key Financial Metrics

The financial analysis for setting up a typical AgriPV project requires consideration of key capex and opex cost elements based on which viability of a project is determined through financial metrics as listed below-

- **Levelized Cost of Electricity (LCOE):** LCOE represents the average revenue per unit of electricity generated that would be required to recover the project costs (CapEx and OpEx) over its lifetime. The LCOE for AgriPV is dependent upon system size, solar radiation, and costs, expected returns, etc.
- **Land Equivalent Ratio (LER):** An LER > 1.0 indicates that the integrated system is more productive than separate solar and agricultural uses on the same total land area.
- **Net Present Value (NPV):** It calculates the present value of future cash flows (both inflows and outflows) over the project's lifetime, discounted at a specific rate (weighted average cost of capital). A positive NPV indicates that the projected earnings generated by a project (in present-day currency) exceed the anticipated costs.
- **Internal Rate of Return (IRR):** IRR is the discount rate that makes the NPV of all cash flows from a particular project equal to zero. It represents the expected compound annual rate of return that will be earned by the project.
- **Payback period:** This metric measures the time required for the cumulative cash inflows from a project to equal the initial investment. A shorter payback period is generally preferred as it indicates quicker recovery of investments.

The illustrative list of assumptions typically required for techno-commercial analysis of AgriPV project is given under Table 52.

Table 52: Table for assumptions typically required for techno-commercial analysis of elevated AgriPV project[68, 69] **Illustrative**

Category	Parameter	Unit	Value (Location and project dependent)
Project Characteristics	Project Capacity	MWdc	10
	Project Life	Years	25
	Construction Period	Months	12
Generation Performance	Capacity Utilization Factor (CUF)	%	22%
	Annual Generation (Year 1)	GWh	19.3
	Module Degradation	%/year	0.50%
CapEx	Total Installed Cost	INR Cr	40-60
	Total Project Cost	USD Mn	5.5-6.5
	Annual Agricultural cost	INR	Agri dependent
Financing Structure	Debt	%	70%
	Equity	%	30%
	Debt Interest Rate	%	9.00%
	Loan Tenure	year	10
Operating Costs	O&M Cost (Year 1)	% of Capex	1%
	O&M Escalation	%/year	3-5%
	O&M for Agri-activities	INR/ha	Agri dependent
Revenue Assumptions	Electricity Tariff Escalation	%/year	5%
	Agricultural Revenue	INR/kWh	Agri dependent
Tax & Finance	Return on Equity (RoE)	%	14-18%
	WACC	%	14%
	Corporate Tax Rate	%	10.50%
Working Capital	Receivables	Months	2
	Working Capital Interest Rate	%	10%

68 Values are indicative only and should not be considered project-specific estimates. Actual costs and returns may vary significantly based on location, system configuration, agricultural practices, market conditions, and financing assumptions. CAPEX assumptions are based on published Indian AgriPV benchmarks.

69 Indo-German Energy Forum (IGEF), National Solar Energy Federation of India (NSEFI), and Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), Agriphotovoltaics in India: Current Status and Future Opportunities, 2020.

Illustrative

Outcome Metric[70]	Unit	Value (Location, project cost and revenue dependent)
Annual Electricity Generation (Year 1)	GWh	19.3
Annual Electricity Revenue	INR Cr/year	8.7-10.6
Additional Agricultural Revenue	INR lakh/year	25-45
Total Annual Revenue	INR Cr/year	9.0-11.0
Equity IRR	%	14-18
NPV @ 10% Discount Rate	INR Cr	Positive
Debt Service Coverage Ratio (DSCR)	x	1.25-1.40 (Good)
Simple Payback Period	Years	5 - 8
Equity Payback Period	Years	4 - 6
LCOE	INR/kWh	3.5-5.0

70 Disclaimer: Illustrative assumptions for modelling purposes only. Actual values may vary based on project location, technology/system configuration, financing structure, market conditions, and regulatory requirements etc. Site specific yield outcomes for crops such as tomato response depends on the amount and conditions of shading.



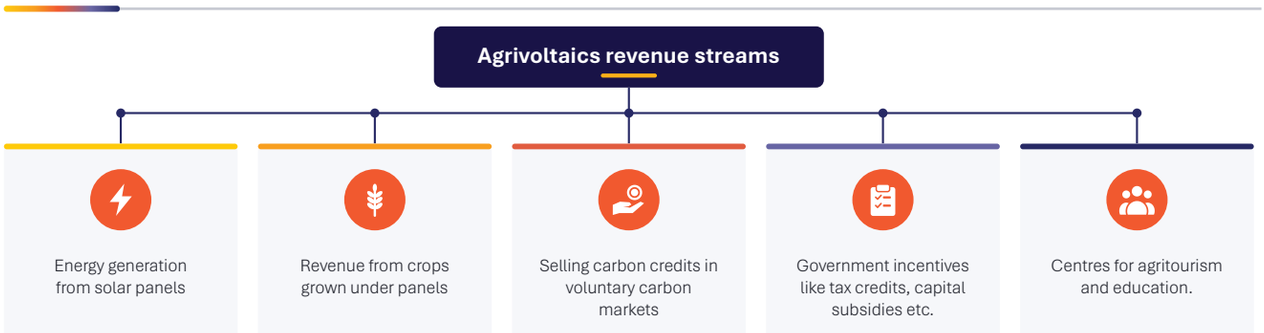


6.3 Revenue Streams & Business / Ownership Models

6.3.1 Revenue streams

The primary revenue streams as shown in Figure 33 can be categorized into (a) energy generation, (b) agricultural production, and (c) ancillary benefits. The revenue streams are explained as follows:

Figure 33: Revenue Streams from AgriPV Systems



Energy Generation:

The most significant and stable revenue stream from AgriPV is the sale of electricity. This is typically achieved through net metering arrangement with Discoms,

Discom direct sales to industrial or commercial consumers through open access agreements.

Agricultural Production

The second major revenue stream is derived from the sale of agricultural products cultivated on the same land. The partial shading provided by solar panels can create a more favourable microclimate for certain crops, leading to increased yields and improved quality, particularly for shade-tolerant varieties like leafy greens, berries, and some root vegetables. For example, studies have shown that crops like lettuce and tomatoes can see yield increases of 12-15% under AgriPV systems[71]. The combination of agricultural sales with electricity generation significantly enhances the overall revenue per acre.

Ancillary Revenue Streams

Beyond energy and crop sales, AgriPV projects can generate income from several other sources:

- **Carbon Credits:** By generating clean energy and potentially sequestering carbon in the soil through improved agricultural practices, AgriPV projects can qualify for carbon credits, which can be sold on voluntary carbon markets.
- **Government incentives and grants:** Various government programs and incentives exist to promote renewable energy and sustainable agriculture. These can include tax credits, grants for project costs (capital subsidy). These are more intended towards cost reduction.
- **Agritourism and education:** AgriPV farms can become centres for agritourism and education, offering farm tours and workshops to generate additional income.

6.3.2 Business / Ownership Models

This subsection analyzes the various structural models for the ownership and operation of AgriPV projects, defining the roles and responsibilities of different stakeholders are summerised in Table 53.

Table 53: Business models for AgriPV systems

Business Model	Asset Owner	Capital Provider	Farmer Revenue Streams	Key Advantages	Key Challenges
Individual Farmer-Owned	Farmer	Farmer (equity/debt)	Crop sales + electricity sales	Maximum value retention and operational control	High capital requirement and technical complexity
FPO / Community-Owned	FPO / Cooperative	FPO, grants, debt	Profit sharing + crop sales	Inclusive participation and risk sharing	Governance and revenue-sharing complexities
Developer-Owned (such as Land Sharing Model, Joint Venture Model Lease-Based Model, PPA-Based Model)	Private developer	Developer	Lease income + crop sales	Minimal farmer investment requirement	Long-term land lease negotiations

71 https://www.sciencedirect.com/science/article/pii/S2405844024120890#:~:text=Abstract,the%20focus%20on%20future%20work.

Table 53: (continued) Business models for AgriPV systems

Business Model	Asset Owner	Capital Provider	Farmer Revenue Streams	Key Advantages	Key Challenges
Discom-Owned	Discom	Utility / public investment	Lease income + crop sales	Reduced burden on farmers and improved grid integration	Utility financing and land acquisition challenges
Open Access Model	Developer / Investor	Private capital	Lease income + crop sales	Higher tariffs and diversified buyers	Regulatory and transmission constraints
FMCG Integrated Model	Developer / Farmer / FPO	Mixed	Crop sales, premium contracts, power-linked benefits	Secured market access and traceability	Demand alignment and supply-chain management
Value-Addition Model	Farmer / FPO	Mixed	Processed products + energy savings	Higher farmgate value realization	Additional infrastructure and operational capability
Clean Fuel Integration	Developer / Energy company	Strategic investors	Crop sales + biomass revenue	Diversified renewable energy production	Technology and market maturity risks
CSR-Funded Model	Farmer / Sponsoring Company	Corporate CSR Funds	Crop sales + access to improved infrastructure and energy benefits	Reduces financial burden on farmers; promotes rural development and sustainable agriculture	Dependent on CSR funding availability; limited scalability and long-term sustainability concerns

AgriPV business models vary in terms of ownership structure, financing arrangements, risk allocation, and revenue-sharing mechanisms. The suitability of a particular model depends on factors such as landholding size, access to capital, institutional capacity, market linkages, and regulatory frameworks.

Similar to operational challenges and mitigation measures, the applicability and effectiveness of each business model may vary across regions and project contexts. A summary of the key business models is presented in this section, while detailed descriptions are provided in Annexure C.5



6.3.3 Financing Case Studies

Funding mechanisms

The economic viability of AgriPV (AgriPV) projects rests on the successful convergence of two traditionally distinct capital-intensive sectors: agriculture and renewable energy. Thus, it also leads to convergence of funding sources from both agriculture and renewable energy sectors. The ability to tap into funding from both sectors is a key enabler for the widespread adoption of AgriPV.

A primary strategy involves the integration of government support across relevant ministries, including agriculture, energy, water, and finance. This entails coordinating policies and financial incentives to create a cohesive support structure for AgriPV development. For instance, agricultural financing programs, such as grants and loans for farm infrastructure, can be combined with renewable energy funds that support the deployment of solar technologies. This synergy allows for a more comprehensive financial package that addresses both the agricultural and energy generation components of a project.

Furthermore, there are significant opportunities to access national and international climate funds. Organizations like the Global Environment Facility (GEF), the Least Developed Countries Fund (LDCF), and the Special Climate Change Fund (SCCF) represent potential sources of capital for AgriPV projects, particularly those that can demonstrate clear environmental and adaptation co-benefits. The alignment of AgriPV with sustainable development goals, such as climate action, food security, and clean energy access, strengthens the case for accessing these funds.

The development of AgriPV specific supportive policies, such as tax incentives, subsidies, risk and credit guarantees, and feed-in tariffs, can further enable the convergence of funding by making AgriPV projects more financially attractive to a wider range of investors.

Financing mechanisms

To address the high upfront costs and perceived risks associated with AgriPV projects, a variety of innovative financing mechanisms are being explored. These include (a) blended finance, (b) mezzanine financing, and (c) green bonds etc., explained in Table 54 and Table 55:

Table 54: Conventional and emerging financing instruments

Financing Instrument	Suitable Models	Key Features
Farmer Equity	Farmer-Owned	Maximum ownership and control, higher investment risk
Bank Debt	Farmer-Owned, FPO-Owned	Traditional project financing through commercial banks and NBFCs
FPO / Cooperative Funding	FPO-Owned	Shared investment burden across members
Developer Equity	Developer-Owned	Private capital investment by project developers
Public Utility Capital	Discom-Owned	Utility-led investments linked to grid infrastructure
Government Subsidies & Grants	All Models	Reduces upfront project costs and improves viability
Corporate PPAs	Open Access, FMCG Models	Long-term revenue certainty through contracted power sales
Blended Finance / Impact Capital	FPO-Owned, Pilot Projects	Combines concessional and commercial capital

Table 54: (continued) Conventional and upcoming financing instrument

Financing Instrument	Suitable Models	Key Features
Green Bonds	Developer-Owned, Discom-Owned, Large FPO Projects	Mobilizes capital for projects delivering environmental benefits, including renewable energy generation and sustainable agricultural outcomes
Climate Finance Funds	Large-scale and Climate-Focused Projects	Access to concessional capital from climate and development institutions

Table 55: Innovative finance for AgriPV case studies

Project	Country	Business Model	Scale	Financing Mechanism	Key Outcomes
Jiangshan AgriPV Park	China	Developer-Owned	Large (>100 MW)	Private developer investment supported by Feed-in Tariff (FiT) revenues	Demonstrated bankability of integrated agriculture, solar generation, and ecotourism at utility scale.
REM TEC AgriPV Portfolio	Italy	Developer-Owned	Large (50-100 MW+)	Developer equity, institutional investors, and project finance debt	Established commercial viability of large-scale AgriPV while retaining agricultural use.
Next2Sun Vertical AgriPV	Germany	Developer-Owned	Medium (1-50 MW)	Developer equity and commercial debt financing	Enabled continued mechanized farming alongside energy production.
Sun'Agri Dynamic AgriPV	France	Farmer-Developer Partnership	Medium (1-50 MW)	Private investment, climate innovation funding, and agricultural finance	Improved crop resilience, reduced heat stress, and enhanced water-use efficiency.
TSE AgriPV Vineyards	France	FMCG / Contract Farming Linked	Medium (1-50 MW)	Private project financing supported by long-term agricultural contracts	Protected high-value crops while generating renewable energy.
Heggelbach AgriPV Project	Germany	Community-Owned / Cooperative	Small (<1 MW)	Research grants, cooperative funding, and institutional support	Demonstrated improved land-use efficiency through dual-use agriculture and solar generation.
Komekurayama Solar Sharing Project	Japan	Farmer-Owned / Cooperative	Small (<1 MW)	Farmer investment supported by renewable energy incentives	Showed compatibility between crop cultivation and solar generation.
SunSeed AgriPV Demonstration	India	Developer-Owned	Small (<1 MW)	Developer investment and institutional support	Demonstrated feasibility of AgriPV under Indian farming conditions.

Table 55: (continued) Innovative finance for AgriPV case studies

Project	Country	Business Model	Scale	Financing Mechanism	Key Outcomes
GroSolar AgriPV Pilot	India	Farmer Participation Model	Small (<1 MW)	Private investment and project partnerships	Validated dual-income opportunities from agriculture and solar generation.
Solar-Powered Cold Storage AgriPV	India	Value-Addition Model	Small-Medium (<5 MW)	Blended finance, subsidies, concessional loans, and FPO/farmer contributions	Improved post-harvest management and reduced food losses.
Green Hydrogen Integrated AgriPV Pilots	ISA Countries	Clean Fuel Integration	Medium-Large (Pilot to 50 MW+)	Climate funds, strategic investors, concessional finance, and green bonds	Created diversified revenue streams through renewable fuel and power production.

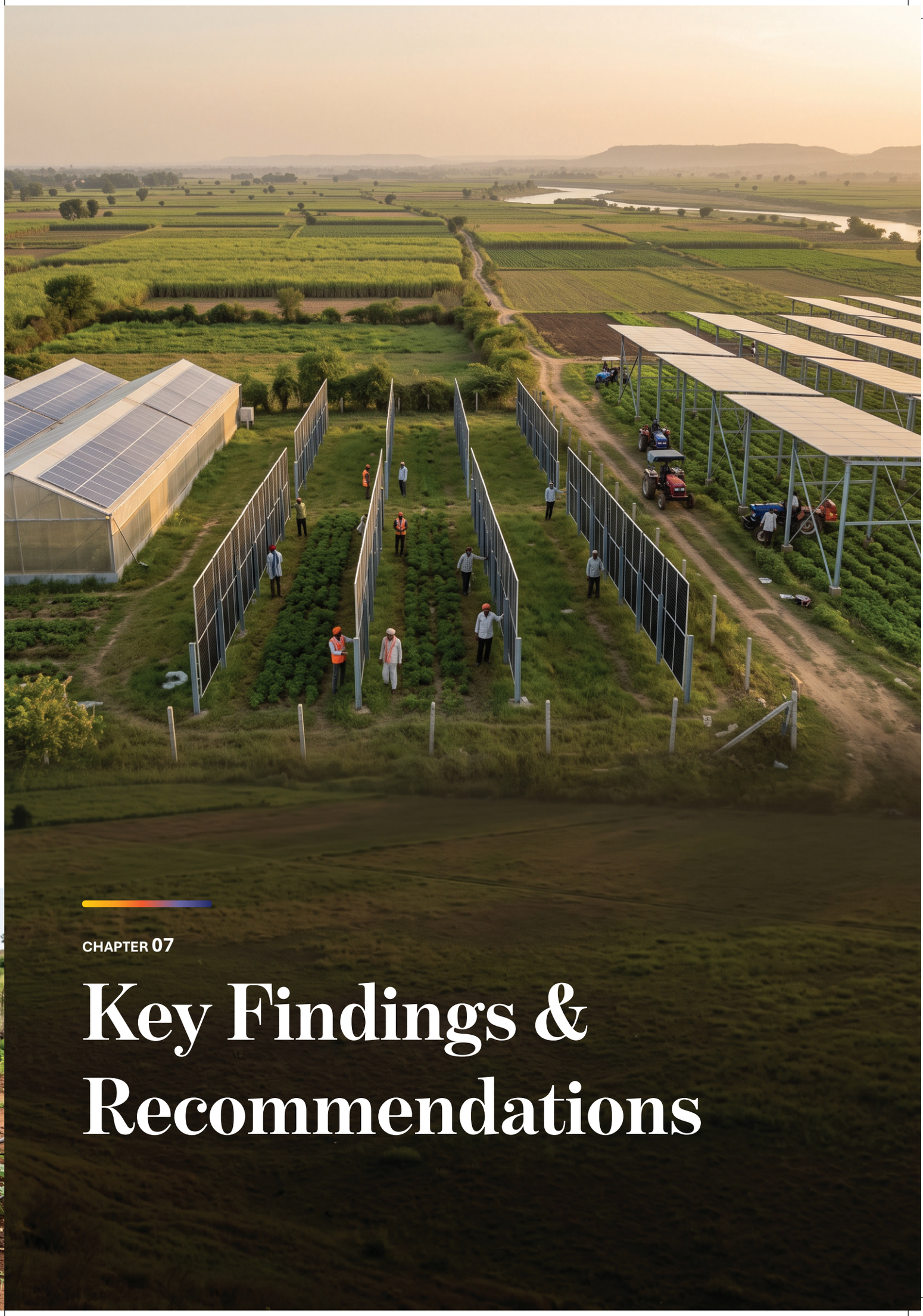
Selected examples of AgriPV projects financed through different funding mechanisms are provided below:

- **Jiangshan, China:** A 200 MW privately-owned commercial scale AgriPV park was developed on degraded farmland with an upfront cost of $312 million USD. The project's profitability was supported by a business model that integrated power generation, agriculture, and ecotourism, and was aided by feed-in-tariff policies that guaranteed revenue from the electricity generated[72].
- **Tanzania:** The "Harvesting the Sun Twice" project, a 35 kWp off-grid AgriPV system, was funded through a £1.3 million GBP grant from the United Kingdom Research and Innovation-Global Challenges Research Fund. This pilot project highlighted the need for innovative financing mechanisms to make the technology accessible to resource-constrained communities[73].

Note: This figure reflects a multi-year research grant covering monitoring, multiple partners, and capacity building and is not a representative commercial CapEx benchmark.

72 https://www.thegef.org/sites/default/files/documents/2024-01/EN_GEF.STAP_.C.66.Inf_.04_Agriphotovoltaics.pdf
73 https://www.sei.org/projects/harvesting-the-sun-twice/





CHAPTER 07

Key Findings & Recommendations

7.1 Cross-Zone Comparison

This section demonstrates three distinct AgriPV system designs, each optimized for different agricultural and environmental contexts. The Elevated AgriPV system prioritizes crop protection and water conservation, making it ideal for harsh climates and high value sensitive crops. The Vertical AgriPV system maximizes land efficiency and machinery access while requiring minimal maintenance, suiting large scale mechanized operations. The Polyhouse AgriPV system offers the most comprehensive environmental control for year-round premium crop production, despite higher initial costs and operational complexity. The key tradeoffs reveal a fundamental principle: systems that enhance crop quality and water conservation require higher investment and expertise, while those maximizing machinery access and energy yield sacrifice some environmental control. Selection depends on prioritizing either resource efficiency (as shown in Table 56) in constrained environments, operational scalability, or production intensity.

Table 56: Profiling of Elevated, Vertical and Polyhouse AgriPV System

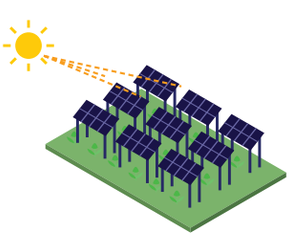
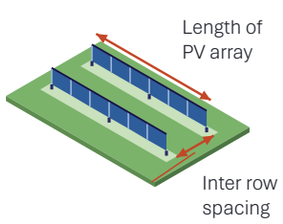
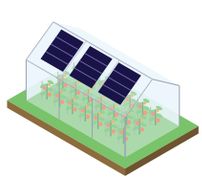
Details	Elevated AgriPV system	Vertical AgriPV system	Polyhouse AgriPV system
			
System profile	Solar panels are mounted high above the ground on a robust structure, creating a protective canopy. Farming occurs directly under the panels.	Bifacial (two-sided) panels are installed vertically in rows, typically oriented North-South or East-West. Farming occurs with near-total freedom between the rows.	A fully integrated greenhouse where semi-transparent solar panels form the roof,
Key advantages	Creates a Protective Microclimate: Shields crops from extreme heat, frost, and hail. Superior Water Conservation: Dramatically reduces evaporation, saving significant amounts of water. Enables High-Value Crops: Makes it possible to grow sensitive crops (leafy greens, berries) in harsh climates. Uniform Land Use: Allows for consistent cultivation across the entire plot.	Maximum Land & Machinery Access: Allows use of large, conventional farm equipment with minimal obstruction. Minimal Midday Shading: Preserves the most productive hours of sunlight for sun-loving crops. Grid-Friendly Power: Produces energy peaks in the morning and afternoon, matching electricity demand. Easy maintenance: Due to the vertical nature of the PV module, it requires minimal cleaning, acts as a windbreak, reduces soil erosion and protects crops from wind damage.	Total Environmental Control: Precise management of temperature, water, and pests. Year-Round Production: Enables multiple harvests per year, independent of external weather. Maximum Resource Efficiency: Exceptionally low water and pesticide use. On-Site Power Generation: Panels power the greenhouse's own fans, pumps, and lights, reducing operational costs.

Table 56: (continued) Profiling of Elevated, Vertical and Polyhouse AgriPV System

Details	Elevated AgriPV system	Vertical AgriPV system	Polyhouse AgriPV system
Key trade-offs	High Initial Cost: Significantly more expensive to build due to the need for more steel and stronger foundations. Complex Maintenance: Panel cleaning and repairs are more difficult and costly at height. Risk of Over-Shading: Poor design can block too much light, requiring careful optimization of panel density. Machinery Constraints: May require specialized, lower-profile farm equipment.	Higher Land Requirement: Needs more land area to achieve the same energy capacity as a conventional solar farm. Higher Technology & Foundation Cost: Requires more expensive bifacial panels and robust foundations to handle wind loads. Directional Shading: Creates significant shadows in the early morning and late afternoon that must be managed. Lower Energy Yield Per Panel: Captures less total energy per day compared to an optimally tilted panel.	Highest Initial Cost: Required for the specialized structure and panels, Complex Heat Management: Prone to overheating, requiring sophisticated cooling and ventilation systems. Reduced Sunlight: Limits the types of crops that can be grown without supplemental lighting. High Operational Expertise: Requires advanced skills in horticulture and climate control systems.
Best suited for	Projects prioritizing water conservation and crop quality in harsh climates (especially arid zones), and for cultivating high-value, sensitive crops where the improved yield justifies the higher investment.	Modernizing large-scale, mechanized farming operations; projects where grid stability and peak power pricing are key economic drivers; and regions where maximizing agricultural access is a higher priority than maximizing energy density.	Specialized producers of high-value, premium crops where year-round supply, quality control, and resource efficiency are the primary goals, and the high initial investment can be justified by high market prices.

AgriPV viability is fundamentally shaped by regional climate conditions (shown in Table 57), with each climate zone presenting distinct design, construction, operations, and agricultural cost drivers. Arid and semi-arid regions face water scarcity challenges requiring integrated irrigation systems and specialized foundations, while tropical systems must manage intense monsoon forces and humidity-related equipment degradation. Temperate and continental climates demand robust structural reinforcement for snow and wind loads, with cold climates imposing additional material and labor costs. The financial burden intensifies across multiple operational areas: maintenance ranges from frequent panel cleaning in dust-prone arid zones to complex vegetation management in tropical systems; agricultural productivity is constrained by climate-specific factors such as reduced light in low-sun temperate zones or heat stress in tropics; and equipment longevity suffers from thermal cycling and environmental corrosion. Successful AgriPV deployment therefore requires climate-appropriate engineering, localized agronomic strategies, and maintenance protocols that account for regional environmental stressors to optimize both energy generation and crop productivity while controlling lifecycle costs.



Table 57: AgriPV Operation and Maintenance by climatic zone

Category	Arid	Semi-Arid	Tropical	Temperate	Continental
Panel Cleaning	Frequent dust removal using water-efficient or dry methods.	Periodic cleaning of dust and agricultural residue.	Remove organic growth, bird droppings and monsoon deposits.	Seasonal removal of pollen, leaves and snow residue.	Snow and ice removal with post-winter inspection.
Vegetation Management	Limited growth; control hardy weeds near foundations.	Seasonal mowing and weed control after rainfall.	Frequent control of fast-growing weeds and climbers.	Routine mowing or managed grazing during the growing season.	Short-season mowing and dry-biomass removal.
Soil Management	Maintain moisture and control wind erosion and salinity.	Monitor uneven moisture, erosion and compaction.	Manage drainage, waterlogging and nutrient loss.	Monitor compaction, drainage and seasonal erosion.	Address freeze–thaw damage and spring waterlogging.
Inverter Maintenance	Clean filters and inspect cooling systems for heat and dust.	Periodic dust cleaning and thermal checks.	Inspect sealing, ventilation and corrosion protection.	Routine diagnostics and seasonal ventilation checks.	Check thermal cycling, condensation and cold-start performance.
Transformer Maintenance	Frequent oil, cooling and dust-ingress checks.	Periodic oil and cooling checks under moderate heat and dust.	Prioritise insulation, moisture-ingress and corrosion checks.	Standard servicing with periodic thermographic inspection.	Seasonal heating, cooling and insulation checks.
Battery System Check	Continuous health monitoring and cooling for high temperatures.	Regular diagnostics for moderate thermal stress.	Check ventilation, sealing and moisture protection.	Routine cycle tracking and preventive maintenance.	Winter heating checks and seasonal performance adjustment.
Solar Trackers	Frequent cleaning, lubrication and alignment checks for dust exposure.	Periodic lubrication and alignment under moderate dust.	Inspect sealing, waterproofing and corrosion protection.	Seasonal mechanical checks and winter de-icing.	Inspect actuators and joints for freeze–thaw misalignment.

AgriPV system longevity and performance efficiency are critically dependent on climate-adapted maintenance protocols across five operational domains. Panel cleaning requirements range from frequent interventions in dust-prone arid zones to periodic servicing in semi-arid and temperate regions, with tropical systems facing accelerated biological fouling. Vegetation management varies significantly, from integrated water infrastructure in arid systems to rapid weed suppression strategies in tropical climates and seasonal crop planning in temperate zones. Inverter maintenance demands escalate in high-humidity tropical and continental environments where moisture ingress and thermal stress necessitate sealed enclosures and advanced ventilation. Transformer and battery systems face climate-specific degradation: arid environments require dust mitigation, tropical zones demand corrosion protection and enhanced cooling, while continental climates need winterization and thermal regulation. Solar tracker maintenance complexity increases with environmental severity, with tropical systems requiring frequent mechanical checks and continental zones demanding

comprehensive seasonal adjustments. Overall, successful AgriPV operation requires proactive, climate-specific maintenance scheduling that anticipates regional environmental stressors including dust storms, humidity, thermal extremes, and biological growth to prevent premature component failure and maintain system reliability and cost-effectiveness throughout its operational lifespan.

7.2 Transferable Design Principles

The design considerations for AgriPV system should be based on a range of agricultural needs to ensure that both energy generation and crop productivity are optimized. The key agricultural needs to consider are described in Figure 34.

Figure 34: Agricultural needs to consider for Agriphotovoltaics system design



Crop selection:
Different crops have varying light, temperature, and moisture requirements. Selecting crops that thrive under particular agrivoltaics design in climatic zone is important for ensuring increased crop quality and yield.

Soil Quality:
Soil health and quality are fundamental to successful crop production. Agrivoltaics system should be designed and installed in manner that ensures minimal soil compaction, soil erosion, and soil disturbance.

Diffused sunlight:
Diffused light from agrivoltaics system can help in providing uniform light distribution on crops underneath the panels. Proper design of agrivoltaics system can help in ensuring uniform light distribution for the crops.

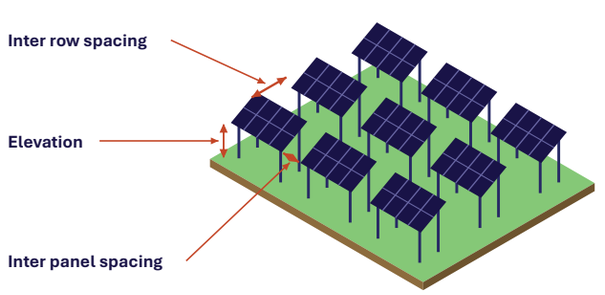
Climatic condition:
Local climate and agrivoltaics system design influences the microclimate under the agrivoltaics. Proper choice of system design is necessary for creating suitable microclimate for crop production.

Water availability:
Agrivoltaics system influences the evaporation rate underneath the panels. Proper design and water management is required for ensuring irrigation requirement and moisture requirement for crop cultivation.

Shade tolerance:
Agrivoltaics system design impacts the shade pattern on the ground as per sun path diagram for the location. Proper design can help ensure proper light/shade requirement for shade benefitting and shade tolerant crops.

For accommodating the above agricultural needs, the AgriPV design considerations are explained below. The key design considerations of inter row spacing, elevation, and inter-panel spacing is shown in Figure 35.

Figure 35: Illustration for mounting height, inter row spacing, and inter panel spacing in Agriphotovoltaics system



The summary of how the above AgriPV design consideration help in facilitating the agricultural needs is described in Table 58

Table 58 Facilitating agricultural needs through AgriPV design considerations

AgriPV design consideration	Crop selection	Climatic condition	Water availability	Shade tolerance	Diffused sunlight	Soil quality
Inter-row spacing	Adjust spacing to accommodate crops with different light and space requirements.	-	Wider spacing can improve water distribution and reduce competition for resources	Optimize spacing to provide appropriate shading levels for shade-tolerant crops.	Optimize spacing to enhance light diffusion and uniformity as required for crops.	Adequate spacing should be provided to prevent soil compaction and allow healthy root growth.
Mounting height	Adjust mounting height to cater to the height and growth patterns of selected crops.	Elevate panels to allow better airflow, reducing humidity and temperature stress.	-	Adjust mounting height to control shade intensity for crops sensitive to light variation.	Adjust mounting height to improve light diffusion across the crop canopy.	Soil characteristics such as moisture retention, nutrient availability and soil temperature are impacted by the mounting height.
Tilt angle	Tilt angle and orientation can be adjusted to suit the light requirements of specific crops based on sun path diagram.	Optimized tilt angle can help enhance airflow and reduce microclimate stress.	-	Adjusting tilt can help in adjusting shade intensity for crops.	Optimized tilt angle can help in having more uniform light distribution across crop area.	-
Inter-panel spacing	Inter panel spacing should be adjusted to accommodate crop light needs and growth patterns. (crop height, canopy)	-	Proper inter panel spacing allows for even rainwater distribution and reduce competition for soil moisture.	Optimize spacing to provide appropriate shading levels for shade-tolerant crops	Optimize spacing to enhance light diffusion and uniformity as required for crops.	Inter panel spacing influences evaporation rate and thus soil moisture.
Panel type	Level of transparency of panel will impact crop selection	Thermal performance and level of transparency of panel will influence microclimate underneath the panels	-	-	-	Lightweight panels can help reduce need for stronger columnar support and thus help reduce soil impact.



Additional Features Supporting Agriculture

- Reflectors: Help distribute sunlight to crops beneath the PV array.
- Rainwater Harvesting Channels: Capture and direct runoff for water conservation while minimizing potential crop damage from concentrated drainage.

Selecting the appropriate layout depends on the specific microclimatic needs of the crops. Different configurations can influence factors such as temperature, humidity, soil type, and light distribution. Below are a few examples illustrating how solar panel layouts impact microclimates across various climate types.

- In **Dry (Arid) Zones**, where extreme heat and water scarcity prevail, solar panels provide critical shade, mitigating soil temperature and reducing evapotranspiration. This fosters a cooler, more humid microenvironment, promoting water conservation and safeguarding crops from heat stress.
- In **Dry (Semi-Arid) Regions**, panels help to moderate temperature fluctuations and reduce wind speeds, which in turn improves soil moisture retention and minimizes erosion.
- In **Tropical Climates**, characterized by intense solar irradiation and intense rainfall, solar panels shield crops from excessive solar radiation and heavy precipitation, preventing leaf scorching and soil erosion while providing a slight cooling effect.
- In **Temperate Zones**, solar panels can extend the growing season by buffering against early frosts and excessive summer heat. They also contribute to stable humidity and soil moisture levels, supporting consistent crop development.
- In **Continental Climates**, marked by extreme seasonal variations, solar panels act as climate buffers, mitigating the impacts of both summer heat and winter cold. This creates a more stable microclimate that protects crops from temperature extremes and wind damage.

The localized microclimate established by solar panels in an AgriPV system is pivotal in determining crop suitability and productivity. By moderating temperature, increasing humidity, reducing wind speed, and enhancing soil moisture retention, this optimized environment can significantly reduce plant stress, boost photosynthetic efficiency, and extend growing seasons.



7.3 Recommendations for ISA Member Countries

Regulatory certainty remains the strongest enabler of AgriPV deployment. Countries such as France, Italy, Japan, and Germany have established clear rules governing dual land use, agricultural compliance requirements, and permitting processes, providing greater confidence to developers and investors.

Financial incentives continue to be the primary catalyst for market growth. Feed-in tariffs, grants, tax incentives, and concessional financing have played a critical role in improving project economics and attracting private capital.

AgriPV is increasingly being incorporated into broader renewable energy and agricultural strategies. National policies are evolving from pilot scale deployment towards commercialization, positioning AgriPV as a mechanism to simultaneously support renewable energy generation, agricultural resilience, and rural income diversification.

Beyond regulations and incentives, ecosystem support is becoming equally important. Countries with strong R&D programmes, technical standards, monitoring frameworks, and stakeholder-capacity building initiatives have generally demonstrated faster market development and improved project performance.

Global experience indicates that successful AgriPV deployment is typically supported by four complementary policy pillars:

1. **Regulatory clarity and dual-use land frameworks**
2. **Targeted financial incentives**
3. **National policy and strategic alignment**
4. **Supporting ecosystem measures including R&D, monitoring, and capacity building**

Countries that combine all four elements have generally demonstrated more mature and scalable AgriPV markets, while reduced development risk and ensuring agricultural productivity is maintained alongside renewable energy generation and given in Table 59.

Table 59: Global best practice with Illustrative Examples in Leading Countries

Best Practice	Description	Illustrative Examples	Leading Countries
Regulatory clarity for dual-use land	Clear AgriPV definitions, land-use eligibility criteria, permitting requirements, and provisions ensuring agricultural production remains the primary land use. Such frameworks reduce project-development uncertainty and improve investor confidence.	France introduced a dedicated AgriPV Framework in 2024; Japan's Solar Sharing model requires continued agricultural activity and farmland retention.	**France, Japan, Italy, Germany**
Distributed generation and grid integration frameworks	Policies enabling self-consumption, net metering, net billing, and distributed renewable energy deployment help reduce reliance on grid infrastructure and improve project viability in rural areas.	India PM-KUSUM supports **500 kW–2 MW** decentralized projects; Kenya's Net Metering Regulations support surplus power export; distributed generation models reduce dependence on transmission infrastructure.	**India, Japan, Kenya, Australia**

Table 59: (continued) Global best practice with Illustrative Examples in Leading Countries

Best Practice	Description	Illustrative Examples	Leading Countries
Agricultural solarisation programmes	Dedicated schemes supporting irrigation pumping, agricultural feeders, cold storage and productive-use applications can accelerate AgriPV deployment while strengthening farm economics.	India PM-KUSUM targets **10 GW** decentralized renewable capacity, **14 lakh stand-alone solar pumps**, and **35 lakh grid-connected agricultural pumps**.	**India, Australia, Kenya**
Financial incentives and revenue diversification	Feed-in tariffs, renewable energy auctions, concessional finance, grants, and agricultural subsidies can improve project bankability and support farmer participation.	Japan's FIT mechanism supports agricultural solar projects; several European markets provide access to renewable energy procurement mechanisms and incentive schemes.	**France, Japan, Germany, Italy, Australia**
Grid connectivity and decentralized deployment models	Promoting behind-the-meter systems for irrigation, cold storage, agro-processing, and rural enterprises can reduce interconnection risks and improve project economics in regions facing grid constraints.	Typical distributed AgriPV systems range from **tens of kW to ~2 MW**, compared to utility-scale projects often exceeding **10 MW**.	**India, Kenya, Japan, Australia**
Agricultural productivity safeguards	Policies requiring continued cultivation, agricultural productivity monitoring, and periodic compliance assessments ensure that solar deployment does not displace agricultural production.	Japan requires continuation of farming activity; France requires demonstrable agricultural benefit and agricultural land protection measures.	**France, Japan**
Research, pilot projects and capacity building	Public support for R&D, demonstration projects, standards development, and farmer training helps build technical evidence and accelerate market adoption.	Pilot programs and research initiatives are supporting crop-specific AgriPV deployment models across multiple ISA and European markets.	**India, Japan, France, Germany, Australia**
Examples for the best practices			
National Policy Support and Strategic Prioritization	AgriPV embedded within energy transition plans, renewable energy targets, agricultural strategies, and land-use planning frameworks.	**France:** Multi-Year Energy Plan (PPE) supports continued growth of solar deployment, including agricultural lands. **Germany:** Renewable Energy Sources Act (EEG) grants special status and streamlined permitting. **Italy:** National tenders have awarded significant capacity for AgriPV development. **Japan:** Green Growth Strategy and carbon neutrality objectives recognize AgriPV as a pathway for sustainable agriculture.	National policy alignment provides long-term market visibility and strengthens investor confidence while supporting renewable energy targets.

Table 59: (continued) Global best practice with Illustrative Examples in Leading Countries

Best Practice	Description	Illustrative Examples	Leading Countries
Supporting Ecosystem Measures	Research and development (R&D), technical frameworks, project monitoring, capacity building, digital aggregation, and knowledge sharing.	**USA:** NREL and DOE provide technical guidance, design standards, and research databases. **Japan:** Periodic project reviews and agricultural yield monitoring. **India:** PM-KUSUM, pilot projects, and collaborative R&D programmes supporting agricultural solar deployment. **EU, Australia and Japan:** Aggregation of distributed energy resources using virtual power plant (VPP) and peer-to-peer models.	Strong institutional support improves project performance, supports innovation, and accelerates market maturity through evidence-based deployment.





7.4 Using the Toolkit

Purpose and Intended Use

The AgriPV Toolkit has been developed as a decision-support resource to help stakeholders evaluate the potential suitability of AgriPV systems across different climatic, agricultural, and operational contexts. Rather than prescribing a single AgriPV model, the toolkit provides a structured framework for assessing site conditions, crop suitability, climate-specific design considerations, operational requirements, and economic factors that may influence project viability (described in Figure 36). It is intended to support informed decision-making during the early planning, screening, and pre-feasibility stages of project development. The toolkit should be used as a guiding framework to identify opportunities, evaluate trade-offs, and facilitate discussions among agricultural, energy, financial, and policy stakeholder

Figure 36: AgriPV Toolkit: Guiding Principles and Stakeholder Applications

Agrivoltaic Toolkit: Guiding Principles & Stakeholder Applications

Guiding Principles for Application

Agriculture as the Primary Design Driver
Crop requirements, seasonal farming cycles, water availability, soil type, and local agricultural objectives must remain the primary inputs to system design. Solar infrastructure configuration—including panel height, tilt angle, row spacing, and shading density—should be determined by what the crop and farm operation demands, not the reverse.

Climate-Specific Decision Making
Agrivoltaic solutions must be tailored to the local climatic envelope, including solar irradiance levels, rainfall patterns, temperature ranges, wind exposure, and humidity. A configuration optimised for arid dryland farming will differ substantially from one designed for humid tropical or temperate rainfed conditions.

Context-Specific Adaptation
Toolkit outputs are starting points, not final prescriptions. They must be interpreted in light of local agricultural practices, crop value chains, national and sub-national regulatory frameworks, land tenure arrangements, water rights, market access conditions, and the socio-economic realities of farming communities.

Integrated Food-Energy Outcomes
The overarching objective is the simultaneous optimisation of agricultural productivity and renewable energy generation. System design, operational protocols, and performance monitoring should target long-run sustainability across both food and energy dimensions, avoiding trade-offs that sacrifice one for marginal gains in the other.

How Different Stakeholders Can Use the Toolkit

Policymakers and Government Agencies
Apply toolkit outputs to inform evidence-based policy development, design targeted agrivoltaic support programmes, guide land-use planning processes, and identify geographic and sectoral priority areas for large-scale deployment aligned with national renewable energy and food security objectives.

Project Developers and Utilities
Use the toolkit for rapid preliminary site screening, early-stage concept development, and structured prioritisation of project opportunities before committing resources to full technical and financial feasibility assessments. Toolkit outputs help narrow the investment pipeline to the most viable configurations.

Farmers and Producer Organizations
Evaluate the compatibility of agrivoltaic systems with existing cropping systems, livestock operations, and farm management practices. Understand the potential implications—positive and adverse—for yields, labour requirements, irrigation needs, and farm income prior to engaging with developers or financing institutions.

Financial Institutions and Investors
Conduct an initial assessment of project-level characteristics including land use, technology configuration, offtake structure, agricultural co-revenue potential, and key risk factors (weather, regulatory, market). Toolkit outputs support preliminary investment screening and due diligence scoping.

Research and Development Organizations
Leverage toolkit frameworks to support pilot project design, define monitoring and evaluation protocols, build local technical capacity, and systematically identify knowledge gaps—agronomic, socio-economic, and engineering—that warrant further applied research investment.

Interpreting Toolkit Outputs: The toolkit should be viewed as a screening and decision-support instrument rather than a predictive model. Outputs should be used to inform preliminary decision-making, guide stakeholder discussions, prioritise sites and design options for detailed evaluation, identify information gaps, and support pre-feasibility assessments. They should not be interpreted as definitive recommendations for project implementation.

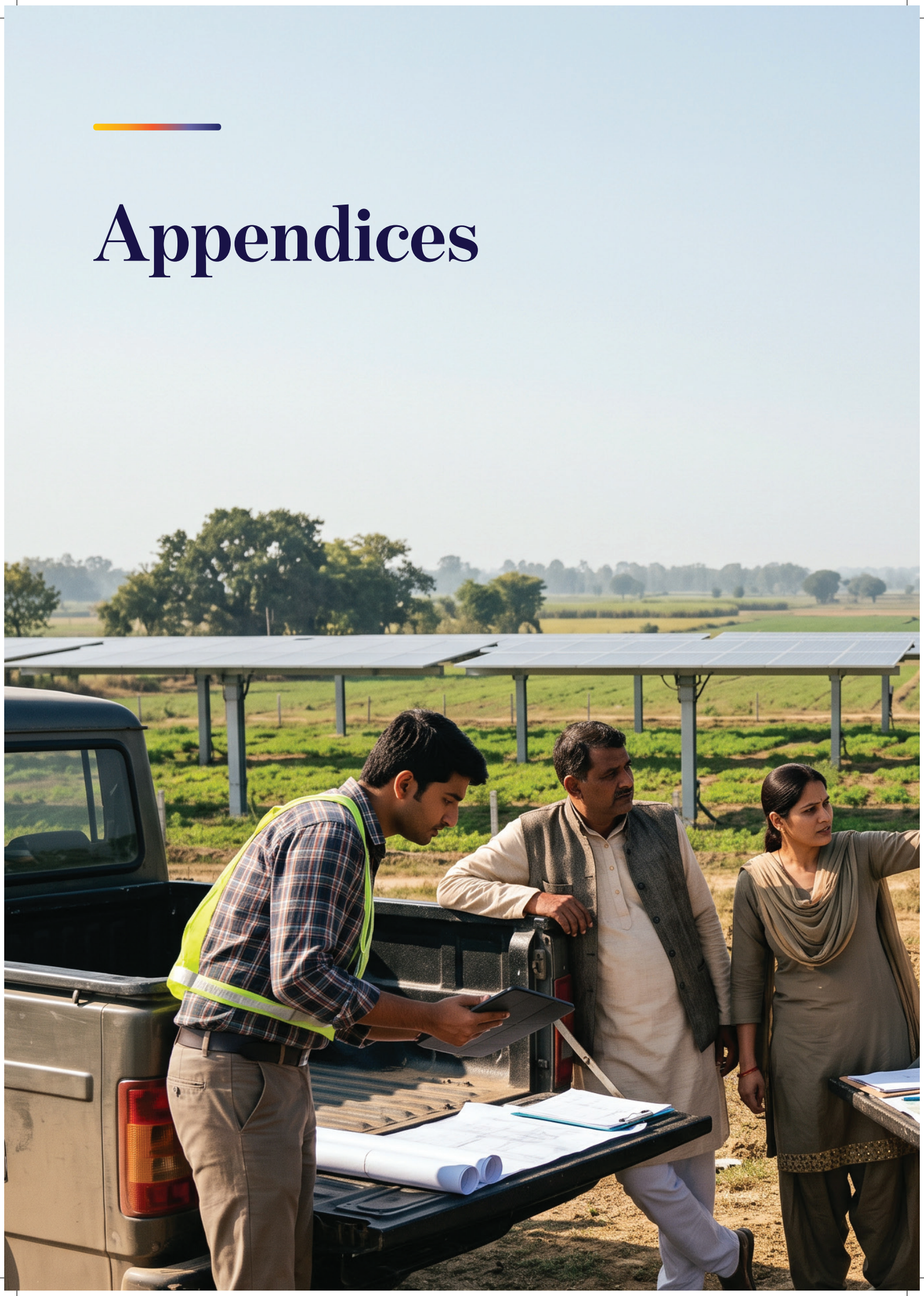
Limitations and Applicability: The toolkit provides generalized guidance across multiple geographies and climatic zones. Local agronomic validation, engineering assessments, regulatory reviews, environmental and social assessments, and investment-grade financial analyses remain essential. Economic outcomes will vary significantly depending on local policies, market conditions, financing structures, and implementation models. Accordingly, the toolkit should be considered a starting point for project development rather than a standalone decision-making instrument.

This publication has been developed using the latest available data and statistics from public and private sources. Reasonable efforts have been made to ensure the information presented is factually correct, accurate, complete, and reliable. However, the ISA does not accept any responsibility or liability for any loss or damage that may occur directly or indirectly from the use of or reliance on the contents of this publication.

The publication is intended solely for informational and research purposes and should not be construed as providing legal, financial, or policy advice. The views expressed are individual opinions and do not necessarily reflect those of the International Solar Alliance. References to specific individuals or entities do not imply endorsement.

The information contained in this publication may be subject to change without notice. The ISA encourages the use of this material for information and research purposes, with appropriate acknowledgement.

Appendices







Appendix A – Stakeholder Consultation & Site-Visit Register

Table A1: Virtual Stakeholder Consultation undertaken during the course of the study

A	Virtual stakeholder consultation	Service Location	Date of consultation
1	AgriTree	Japan	9 July 2025
2	BayWa r.e	Europe and North America	9 July 2025
3	ENVELOPS	**Indonesia, Vietnam, Fiji, others project -** Jamaica and European, Netherlands and France	8 July 2025
4	Gro Solar Energy Private Limited	India	7 August 2025
5	Khare Energy	India	24 June 2025
6	Next2Sun Technology GmbH	Germany, Austria, France	8 July 2025
7	Renkube Pvt. Ltd.	India	19 May 2025
8	Jaipur Vidyut Vitaran Nigam Limited	India	20 May 2025
9	Madhya Pradesh New and Renewable Energy Department (MPNRED)	India	19 September 2025

Table A1: (continued) Virtual Stakeholder Consultation undertaken during the course of the study

A	Virtual stakeholder consultation	Service Location			Date of consultation
10	Egypt (Ministry of a) Electricity and Renewable Energy, b) Agriculture and Land Reclamation, and c) Water Resources and Irrigation)	Egypt			10 December 2025
B	**Physical stakeholder consultation**	**Location**	**Climate Zone**	**System size**	**Date of consultation**
1	Mr. Manish Khare- Sagar, MP	Sagar, Madhya Pradesh, India	**Semi-arid**	4.5 MWp	23 September 2025
2	Mr. Balaji BL, Renkube Hyderabad	PJSTAU and Renkube , Hyderabad	**Tropical**	10.8 kWp	21 November 2025
3	Mary Pauly- CIAL, Cochin	Cochin International Airport, Kochi, India	**Tropical**	2 MW	20 November 2025
4	CAZRI	Jodhpur	**Arid**	100 kWp	18 June 2026



Appendix B – Köppen– Geiger Classification Details

Below is a comprehensive comparison matrix for all subtypes of the Köppen-Geiger classification system. The matrix covers global distribution, temperature range, precipitation, vegetation, and human activities, tailored to be detailed yet concise for each subtype. This ensures a thorough comparison across all Köppen classifications:



Table B1: Comprehensive comparison matrix for all subtypes of the Köppen–Geiger classification system

S. N	Climate Zone	Köppen Code	Global Distribution (Key Regions)	Temperature Range	Precipitation	Vegetation	Human Activities
1	Tropical Rainforest	Af	Amazon Basin (Brazil: Amazonas, Pará; Peru: Loreto, Ucayali; Colombia: Amazonas), Congo Basin (Democratic Republic of Congo: Congo Central, Equateur; Republic of Congo: Sangha), Indonesia (Kalimantan, Sumatra, Papua), Malaysia (Sarawak, Sabah)	Warm year-round (>18°C coolest month)	>2000 mm, no dry season (>60 mm monthly)	Dense rainforests, high biodiversity	Forestry, subsistence agriculture, ecotourism
2	Tropical Monsoon	Am	South Asia (India: West Bengal, Assam, Kerala; Bangladesh: Chittagong, Sylhet), West Africa (Nigeria: Lagos, Cross River; Ghana: Ashanti, Western Region), Northern Australia (Queensland: Cairns, Darwin)	Warm year-round (>18°C coolest month)	1000–2000 mm, distinct wet/dry seasons	Seasonal forests, mangroves	Rice cultivation, fishing, urban development
3	Tropical Savanna	Aw/As	East Africa (Kenya: Rift Valley, Eastern; Tanzania: Dodoma, Arusha), Northern Australia (Queensland: Townsville, Northern Territory: Katherine), Brazil (Mato Grosso, Goiás), India (Maharashtra: Vidarbha, Karnataka: Northern Plateau)	Warm year-round (>18°C coolest month)	800–1500 mm, pronounced dry season	Grasslands, savannas, scattered trees	Pastoralism[74], agriculture (cereals), wildlife tourism
4	Hot Desert	BWh	Sahara (Algeria: Tamanrasset; Egypt: Western Desert; Libya: Fezzan), Arabian Peninsula (Saudi Arabia: Rub' al Khali; UAE: Abu Dhabi), Atacama (Chile: Antofagasta, Atacama Region), Central Australia (Northern Territory: Simpson Desert; South Australia: Great Victoria Desert)	Hot year-round (>18°C mean annual), extreme summers (>40°C)	<200 mm, highly erratic	Sparse shrubs, cacti	Nomadic herding, mining, oasis agriculture
5	Cold Desert	BWk	Gobi (Mongolia: Gobi-Altai, Bayankhongor; China: Inner Mongolia), Great Basin (USA: Nevada, Utah), Patagonia (Argentina: Santa Cruz, Chubut)	Cold winters (<0°C), hot summers (up to 35°C)	<200 mm, often winter snow	Sparse shrubs, hardy grasses	Limited agriculture, mining, pastoralism

74 Pastoralism involves raising domesticated animals like cattle, sheep, goats, and camels for livelihood of the people, typically on open ranges or pastures

Table B1: (continued) Comprehensive comparison matrix for all subtypes of the Köppen–Geiger classification system

S. N	Climate Zone	Köppen Code	Global Distribution (Key Regions)	Temperature Range	Precipitation	Vegetation	Human Activities
6	Hot Semi-Arid	BSh	Sahel (Nigeria: Borno, Yobe; Mali: Timbuktu, Gao; Niger: Agadez), Central Australia (Northern Territory: Alice Springs; Queensland: Outback), India (Rajasthan: Thar Desert, Gujarat: Kutch), Northern Mexico (Chihuahua: Chihuahuan Desert; Sonora: Sonoran Desert)	Hot summers (>40°C), mild winters (>18°C mean annual)	200–500 mm, erratic, often monsoonal	Grasses, shrubs, drought-tolerant trees (e.g., acacia)	Pastoralism, irrigated agriculture (millet, sorghum), nomadic herding
7	Cold Semi-Arid	BSk	Great Plains (USA: Kansas, Nebraska, eastern Montana), Patagonia (Argentina: Rio Negro, Neuquén), Central Asia (Kazakhstan: Kyzylorda, Almaty; Mongolia: Uvs, Zavkhan), Iran (Kerman Province, Sistan and Balochestan)	Hot summers (up to 35°C), cold winters (down to -20°C)	200–500 mm, seasonal (spring/summer)	Short grasses, steppes, hardy shrubs	Livestock grazing, dryland farming (wheat, barley), ranching[75]
8	Mediterranean Hot Summer	Csa	Southern Europe (Spain: Andalusia, Murcia; Italy: Sicily, Puglia), USA (California: Central Valley, Southern California), Central Chile (Santiago, Valparaíso Regions), Southern Australia (South Australia: Adelaide Plains; Western Australia: Swan Valley)	Hot summers (>22°C warmest month), mild winters (>-3°C, <18°C)	400–1000 mm, dry summer, wet winter	Scrublands[76], olive trees, chaparral [77]	Viticulture[78], tourism, urban centres
9	Mediterranean Warm Summer	Csb	USA (California: Coastal Monterey, Sonoma), Portugal (Douro Valley, Alentejo), South Africa (Western Cape: Cape Town, Stellenbosch)	Warm summers (<22°C warmest month), mild winters (>-3°C, <18°C)	400–800 mm, dry summer, wet winter	Scrublands, pine/oak woodlands	Agriculture (grapes, citrus), tourism
10	Temperate Oceanic	Cfb	Western Europe (UK: Scotland, Wales; Ireland: Munster, Connacht), New Zealand (South Island: Canterbury, Otago), Canada (British Columbia: Vancouver Island, Coastal BC)	Cool summers (<22°C warmest month), mild winters (>-3°C, <18°C)	800–2000 mm, even distribution	Deciduous/coniferous forests	Mixed farming, forestry, urban development

75 Ranching refers to managing and caring for a herd of animals-such as cows, sheep or goats-on a grazing area to produce milk, meat, or other animal products
76 Scrubland is an area which is covered with low trees and bushes
77 Chaparral is a dense, thorny thicket ecosystem characterized by drought-tolerant, evergreen shrubs and small trees
78 Viticulture refers to the cultivation and harvesting of grapevines

Table B1: (continued) Comprehensive comparison matrix for all subtypes of the Köppen–Geiger classification system

S. N	Climate Zone	Köppen Code	Global Distribution (Key Regions)	Temperature Range	Precipitation	Vegetation	Human Activities
11	Temperate Continental Hot Summer	Cfa	USA (Southeastern states: Georgia, Alabama, Mississippi), China (Eastern: Jiangsu, Zhejiang), Japan (Honshu: Kanto, Kansai), Argentina (Northern: Santa Fe, Córdoba)	Hot summers (>22°C warmest month), mild winters (>-3°C, <18°C)	800–1500 mm, even or summer-max	Deciduous forests, grasslands	Agriculture (corn, soybean), urban centres
12	Temperate Continental Warm Summer	Cwa	India (Northern: Uttar Pradesh, Bihar), China (Southern: Yunnan, Sichuan), Brazil (Southern: São Paulo, Paraná)	Warm summers (<22°C warmest month), mild winters (>-3°C, <18°C)	600–1200 mm, dry winter, wet summer	Mixed forests, grasslands	Agriculture (rice, wheat), urban development
13	Cold Continental Hot Summer	Dfa	USA (Northeastern: New York, Pennsylvania), China (Northern: Heilongjiang, Jilin), South Korea (Gangwon, Gyeonggi)	Hot summers (>22°C warmest month), cold winters (<-3°C)	500–1000 mm, even or summer-max	Mixed forests, grasslands	Grain farming, urban centers, industry
14	Cold Continental Warm Summer	Dfb	Canada (Alberta: Calgary, Saskatchewan), Scandinavia (Sweden: Västerbotten; Norway: Trøndelag), Russia (Siberia: Krasnoyarsk, Irkutsk)	Warm summers (<22°C warmest month), cold winters (<-3°C)	400–800 mm, even or summer-max	Boreal forests (taiga)	Forestry, mining, limited agriculture
15	Cold Continental Dry Winter	Dwa/Dwb	Siberia, northern China, Mongolia	Hot/warm summers, very cold winters (down to -30°C)	300–700 mm, dry winter, wet summer	Boreal forests, steppes	Nomadic herding, mining, forestry
16	Tundra	ET	Arctic regions (Alaska, northern Canada, Greenland), Antarctic coast	Cool summers (<10°C warmest month), cold winters	150–400 mm, mostly snow	Tundra (mosses, lichens)	Indigenous hunting, research, tourism
17	Ice Cap	EF	Antarctica interior, Greenland interior	Always <0°C	<100 mm, mostly snow	None	Scientific research



Appendix C – Technical Reference

C1. Challenge Mitigation Matrix

Mitigation Plan for Challenges

For each identified operational challenge in AgriPV projects, a targeted mitigation plan has been formulated to reduce both the probability of occurrence and the severity of impact. These plans include preventivemeasures such as improved design standards, regular maintenance schedules, environmental controls, and contingency protocols tailored to specific climatic zones. After implementing these mitigation strategies, a residual risk assessment can ensure that even after mitigation, any residual exposure is clearly understood and documented, allowing decision-makers to determine whether additional controls are required or if the risk is acceptable within project thresholds.

Table C1: Challenge Mitigation Matrix for different climatic zones

Challenge	Arid	Semi-Arid	Tropical	Temperate	Continental
Dust accumulation	Soiling monitoring should be frequent and if possible, through sensors. It will help to schedule timely cleaning. Use windbreaks, optimise panel tilt,	Install soiling sensors, schedule frequent dry brushing/robotic cleaning, and optimise the tilt angle of PV panels.	Leverage rain cleaning, but monitor biological soiling (bird droppings, pollen); targeted manual cleaning post-events.	Seasonal pollen/bird controls, periodic inspection; maintain vegetation to reduce dust resuspension	Focus on spring pollen; schedule cleaning around windy/hail seasons; protect washing from freeze.[79]

79 In continental or temperate climates, washing during sub-zero temperatures can cause water to freeze on panels, leading to ice formation, micro-cracks, or slippery work conditions.

Table C1: (continued) Challenge Mitigation Matrix for different climatic zones

Challenge	Arid	Semi-Arid	Tropical	Temperate	Continental
Dust accumulation	and apply predictive cleaning strategies based on soiling trend analysis through climatology or multi-year reanalysis data.				
Data connectivity	Install active cooling or ventilated enclosures for electronics, and regular dry cleaning or automated cleaning is required for panels and sensors.	Install active cooling or ventilated enclosures for electronics, and regular dry cleaning or automated cleaning is required for panels and sensors. Periodic inspection after seasonal rains for corrosion and insulation integrity.	Use weather-resistant components with protective coatings to safeguard against moisture ingress. Schedule regular cleaning to prevent organic buildup on equipment. Additionally, implement wildlife deterrent measures such as metal mesh or protective conduits to minimise the risk of cable damage.	Essential to manage seasonal variations that cause condensation and occasional frost. Install humidity-controlled enclosures equipped with desiccants to prevent moisture build up inside communication hardware. Adjust panel tilt for snow shedding, install freeze-thaw rated cables, and perform regular inspections to maintain insulation integrity.	Place monitoring devices and junction boxes in sheltered or indoor areas to protect them from snow and ice. Integrate IoT sensors to monitor snow accumulation and activate removal systems when needed. Strengthen mounting structures to endure heavy snow loads and safeguard wiring and communication components from damage.
Transformer failure	Use forced-air cooling systems (ONAF) or liquid-immersed transformers to withstand higher temperatures. Select sealed, weather-resistant enclosures with high IP ratings to prevent dust ingress. Regularly	Plan seasonal cleaning and inspections and apply anti-fouling coatings on insulators to prevent contamination. Install wildlife guards, protective conduit armour, and terminal covers to	Use moisture-resistant enclosures. Ensure breather systems with functional silica gel[80] are installed and regularly maintained/ replaced to absorb moisture. Apply special anti-corrosion coatings or paints on the tank body and use	Install humidity-controlled enclosures with heaters or desiccants and use IP-rated glands and seals to prevent moisture ingress. Choose cables and gaskets designed for freeze–thaw conditions and perform routine checks for	Use low-pour-point oils[81] and cold-rated materials to ensure reliable operation in extreme cold. Install preheaters or space heaters in control cabinets, provide shelters for transformers

80 A transformer's breather system with functional silica gel is a device that prevents moisture from entering the transformer during its heating and cooling cycles. It works by using silica gel, a desiccant, to absorb moisture from the air as it passes through the breather before entering the conservator tank. This protects the transformer's insulating oil and internal components from corrosion and degradation

81 Low-pour-point transformer oils are specialized fluids designed to remain liquid and flow at very cold temperatures, preventing transformer failure in cold climates. These oils, often naphthenic mineral oils or synthetic esters, have a low wax content, which ensures they do not solidify and block circulation, maintaining the transformer's cooling and insulation capabilities in frigid environments.

Table C1: (continued) Challenge Mitigation Matrix for different climatic zones

Challenge	Arid	Semi-Arid	Tropical	Temperate	Continental
Transformer failure	clean cooling fins and external surfaces.	safeguard against animal interference. Upgrade surge arresters, maintain robust earthing.	stainless steel fittings to mitigate rust and damage.	micro-leaks and condensation. Optimise cooling systems and adopt condition-based maintenance using load and temperature trend analysis.	and auxiliary boxes, and reinforce mounting structures. Conduct regular functional checks of heaters and fans to maintain performance.
Corrosive environment	Use galvanised or stainless-steel hardware and apply anti-corrosion coatings on exposed surfaces. Schedule periodic dry cleaning of fins and bushings to remove dust and contaminants before they react with moisture.	Use galvanised or stainless-steel hardware and apply anti-corrosion coatings on exposed surfaces. Inspect after rainy seasons to check if dirt has accumulated and remove contaminants before they react with moisture.	Use insulated coatings and stainless-steel components. Wash insulators regularly with demineralised water. Maintain breathers and replace desiccants frequently to control moisture ingress.	Install humidity-controlled enclosures with heaters or desiccants and IP-rated seals. Use corrosion-resistant gaskets and perform routine checks for condensation and micro-leaks. Apply protective coatings on metallic parts exposed to weather.	Provide shelters for transformers and auxiliary boxes to limit exposure. Use stainless steel fasteners and apply anti-corrosion grease on terminals. Conduct seasonal inspections after snow melt to detect early signs of rust.
Power Curtailment	Schedule irrigation and pumping during peak hours using variable-speed drives. Add a BESS system to absorb excess energy.	Align irrigation and crop processing with solar peaks and add a BESS system to store excess energy.	Add a BESS system to store excess energy during solar peaks.	Add a BESS system to store excess energy during solar peaks.	Add a BESS system to store excess energy during solar peaks.
Extreme temperatures	Use panels with tough glass and dust-resistant coating. Add wind barriers and tighten mounts often. Keep electronics in ventilated, dustproof boxes. Clean panels with soft brushes or air blowers.	Check and clean panels after storms. Use waterproof seals on cables and boxes. Install surge protectors for lightning. Make sure mounts are strong enough for wind.	Use rust-proof frames and marine-grade parts. Raise inverters off the ground to avoid damage from possible flooding. Wash panels to remove dirt particles after rain/storm/hail. Use strong mounts for cyclone winds and panels tested for hail.	Choose panels tested for hail. Tilt panels so snow and water slide off. Use waterproof boxes with heaters to stop damage from moisture ingress. Add lightning protection.	Use strong mounts and snow guards. Pick panels with thick glass for hail. Add heaters in control boxes and shelters for equipment. Check mounts and panels after big snowstorms.

Table C1: (continued) Challenge Mitigation Matrix for different climatic zones

Challenge	Arid	Semi-Arid	Tropical	Temperate	Continental
Water Quality	Use drip filters and flush lines regularly. Clean panels with demineralised/ soft water; avoid borewell water for panel washing. Choose salt-tolerant crops where needed.	Test TDS monthly; install good filtration systems. Wash panels with soft/ treated water. Use soil leaching/ gypsum where salinity rises.	Use corrosion-resistant materials (stainless/HDPE). Raise pumps/panels away from salt spray. Rinse panels with fresh water, not seawater. Check TDS after storms; consider rainwater harvesting to dilute high-TDS sources.	Keep a TDS log and fit a basic softening/ anti-scalant for hard water. Use appropriate filters and scheduled descaling. Clean panels with soft water and a squeegee to prevent spotting.	Insulate lines, use cold-compatible antiscalants[82], and flush regularly. Store soft/treated water for panel cleaning. Do descaling during warmer months when treatments work better.
Reduced Light Distribution	Leverage shade as a benefit to reduce heat stress and water use. Use a fixed-tilt system or single-axis trackers programmed to provide maximal shade during the hottest parts of the day. This protects crops and significantly improves water efficiency.	Utilize single-axis trackers to follow the sun and adjust light exposure, or vertical bifacial panels to capture morning/afternoon sun while leaving the midday path clear. The design focus is on providing enough light for staple crops, not maximum light.	Maximize light during the cooler, often overcast, spring and autumn growing seasons. Wider panel spacing is critical. Vertical bifacial panels are also highly effective here, as they leave the direct overhead sun path open for crops while capturing high-value morning and evening sun for energy.	Ensure sufficient light while prioritizing ventilation. A standard fixed-tilt system with moderate spacing is often sufficient. The key is to integrate the design with ventilation needs, ensuring the panel layout does not trap humidity.	Single-axis or dual-axis trackers are the most effective solution. They can be programmed to provide shade in the summer but shift to maximize sun exposure in spring and fall to warm the soil and accelerate growth. In winter, they can be tilted steeply to shed snow, preventing structural damage and allowing sunlight to reach the ground.
Uneven Water Distribution	Use drip irrigation or micro-sprinklers to deliver water specifically to the dry zones directly under the panels. Improve soil organic matter and structure to increase its water-holding capacity and infiltration rates.	Guttering systems are essential. The captured runoff should be channelled into storage tanks. This stored water can then be used to feed a drip irrigation system, efficiently delivering water to the crop roots in	Design the field with engineered swales or subsurface drainage tiles between the rows to quickly channel away the concentrated runoff. Elevating the panels higher can also help with airflow and drying, but managing ground-level waterlogging is the	A combination of targeted drip irrigation for the dry areas and ensuring good soil structure is often sufficient. For high-value crops, modest drainage systems in the runoff pathways may be cost-effective.	The site design must include robust water management features like graded swales or small retention ponds to handle the sudden influx of water from melting snow. This prevents widespread

82 Special chemicals that stop mineral buildup (scale) in pipes, even when it's very cold.

Table C1: (continued) Challenge Mitigation Matrix for different climatic zones

Challenge	Arid	Semi-Arid	Tropical	Temperate	Continental
Uneven Water Distribution		the dry zones under the panels.	primary goal.		erosion and waterlogging at the start of the growing season.
Limitation in machinery access	Pre-Installation Planning: The design process must begin with a detailed survey of the farm's current and future machinery fleet. All row spacing, headlands, and vertical clearances must be specified before the first post is installed. Increased Mounting Height: Raising the vertical clearance of the panels is the most direct way to accommodate taller machinery like modern tractors and harvesters. Wider Post Spacing: Utilize structural designs (e.g., steel beams, cable-suspension) that allow for longer spans between support columns, creating open corridors for machinery. Foundation Placement: For root and tuber crops (e.g., potatoes), support foundations must be meticulously planned to be outside the path of digging and harvesting equipment.				
High Humidity & Precipitation	Rare rains but sudden storms can occur, so use sealed boxes and weatherproof connectors; apply anti-corrosion coatings on metal parts.	Seasonal rains might occur, so use waterproof enclosures and cable glands; inspect for rust after storms.	Heavy rain and salt air can occur, so marine-grade materials, rust-proof coatings, and raise inverters above fl level; clean panels remove algae and salt from time to time. useto ood	Frequent rain and frost are a possibility, so install humidity-controlled enclosures with heaters or desiccants; check seals after heavy rain.	Shelter equipment to protect from ice and snow melts, use heaters in control boxes, and waterproof seals to prevent freeze damage.
Wind and hail	High winds and sandstorms can be frequent, so install strong mounting structures and wind barriers.	Reinforce racking, tighten fasteners before storm season, and use hail-tested panels to protect from gusty winds and occasional hail.	Use cyclone-rated racking, deep foundations, and hail-resistant panels; set trackers to safe angles during storms.	Choose hail-tested panels, optimise tilt for snow/hail shedding, and reinforce mounts; lightning protection. add	Strengthen mounts for snow loads, use hail-resistant glass, and maintain a steeper tilt of panels for snow shedding.
Icing and snowing	There are temperature drops during winters but there is no significant treat of icing and snowing in such regions.	There are temperature drops during winters but there is no significant treat of icing and snowing in such regions.	Tropical zones are generally warm year-round, and there is no threat of icing snowfall. and	Mitigation measures include using steeper panel tilt angles for natural snow shedding, installing robust mounting structures to handle snow loads, adding heaters in control boxes, and applying waterproof seals on equipment and cables to prevent freeze damage.	Mitigation measures include mounting panels on adjustable or elevated structures to prevent snow buildup and maintain space for farming, using dynamic tilt systems for effective snow shedding, and ensuring enhanced

Table C1: (continued) Challenge Mitigation Matrix for different climatic zones

Challenge	Arid	Semi-Arid	Tropical	Temperate	Continental
Icing and snowing					structural load capacity. Additional steps involve installing heaters in control boxes, applying waterproof seals on equipment and cables to avoid freeze damage, and implementing comprehensive winterization protocols supported by predictive maintenance and localized weather forecasting.
Uneven terrain	Apply grading and levelling in critical areas, combined with modular mounting systems that adapt to slope variations; prioritize erosion control.	Apply grading and levelling in critical areas, combined with modular mounting systems that adapt to slope variations; prioritize erosion control.	Apply grading and levelling in critical areas and incorporate drainage systems to manage heavy rainfall and prevent soil washout.	Deploy flexible racking systems with adjustable tilt and height; minor grading may be needed for rolling hills to maintain uniform panel alignment.	Adopt elevated or adjustable mounting frames for uneven plains and frost-prone soil; reinforce foundations to withstand seasonal freeze-thaw cycles.
Pests and Diseases	Install cable conduits, mesh guards, and keep vegetation trimmed to reduce nesting.	Install wildlife guards, apply pest deterrents, and maintain clean surroundings to prevent damage.	Apply anti-termite treatment near foundations, seal conduits, and inspect regularly for pest entry points.	Frequent trimming of grass and shrubs might be required, use cable guards, and apply insect deterrents near control boxes.	Install rodent-proof conduits, apply pest deterrents in storage areas, and inspect wiring regularly.
Lack of skilled labour	Skill matrices, certification, digital O&M manuals, spares/asset registry clarity.	Standardised O&M procedures, checklists, remote support, and local contractor training.	Weather-specific SOPs (flood/cyclone); cross-training with farm staff for basic inspections.	Routine skills audits; refresher training; data-driven task scheduling.	Winter operations training, safety drills for hail/wind; remote diagnostics tools.

C2. Assessment Methodology and Tools

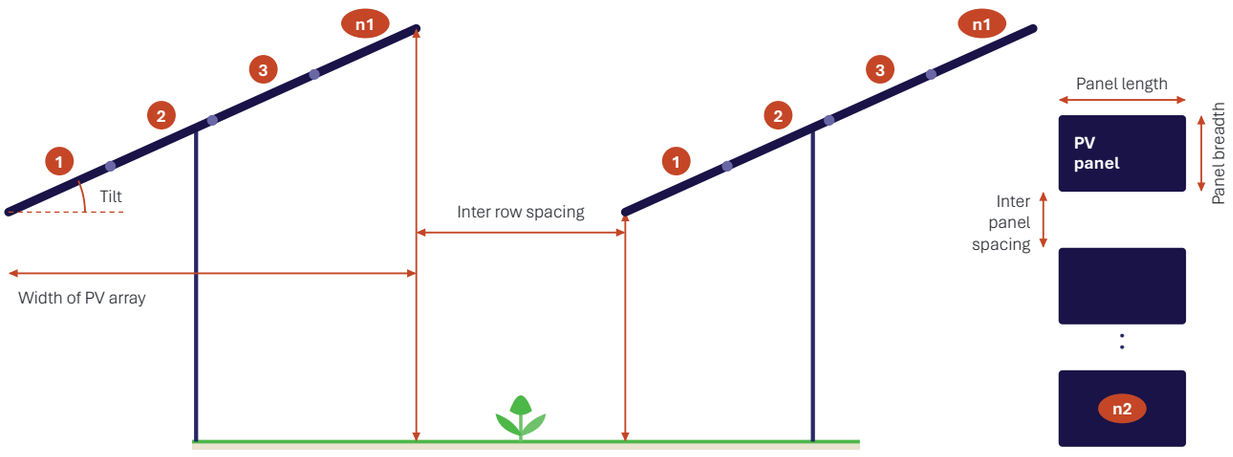
i. Assessment Methodology

Elevated and polyhouse AgriPV orientation

This subsection includes methodology for estimating the PV system capacity for following AgriPV layouts: (a)elevated, and (b) polyhouse, as these layouts are oriented horizontally.

In AgriPV planning, system sizing is undertaken through a structured, stepwise methodology that converts the chosen structural and layout parameters into an estimate of maximum DC capacity. The calculations given in this subsection provide a generic framework for this process. The graphical representation of an elevated layout is shown in the Figure 37.

Figure 37 Illustration of elevated Agriphotovoltaics orientation



The parameters along with metrices which needs to be considered for capacity sizing based on design considerations pertaining are given in below table.

Table C2: Key metrices for capacity sizing based on design considerations- Eleveated and Polyhouse AgripV orientation

Parameter	Metrices	Rationale
Panel length	"l' metres	Standard dimension of a single PV panel.
Panel breadth	"b" metres	Standard dimension of a single PV panel.
Tilt of PV Array	"θ" degrees	Angle at which the PV array is inclined relative to the horizontal plane to optimize solar energy capture. This angle is crucial for maximizing irradiance and minimizing shading, especially for horizontal arrays.
Inter row spacing between two PV arrays	"d" metres	Horizontal distance between consecutive PV arrays. This spacing is critical to mitigate inter-row shading and ensure adequate light penetration for agricultural activities beneath and between arrays.
Inter panel spacing along the width of the PV array	"p_1 " metres	Horizontal distance between individual PV panels along the width of an array. For increasing light penetration for agricultural activities beneath the array.

Table C2: (continued) Key metrices for capacity sizing based on design considerations- Eleveated and Polyhouse AgripV orientation

Parameter	Metrices	Rationale
Inter panel spacing along the length of the PV array	"p_2" metres	Horizontal distance between individual PV panels along the length of an array. For increasing light penetration for agricultural activities beneath the array.
Number of panels along the width of the PV array	"n_1" units	Determines the overall width of the PV array.
Number of panels along the length of the PV array	"n_2" units	Determines the overall length of the PV array.
Panel alignment on the PV array	Portrait (panel length along the width of the PV array)	Specific orientation of individual panels within the array, impacting array dimensions and shading characteristics.
Additional space requirement	"s%"	Percentage of additional area required to accommodate ancillary infrastructure such as pathways, land topography variations, and the installation of critical electrical components including junction boxes, inverters, transformers, and battery storage systems. This factor is essential for practical deployment and operational efficiency.
Rated capacity of panel	"C" Watts	The nominal power output of a single PV panel under Standard Test Conditions (STC).

From these parameters, the following calculations are performed to evaluate the system capacity:

- **Length of the PV array (L):** This dimension is calculated by considering the panel breadth (b) aligned along the array's length, the inter-panel spacing along the length (p_2), and the number of panels along the length (n_2).

  $$L = n_2 * b + (n_2 - 1) * p_2$$

- **Width of the PV array (W):** This dimension is calculated by considering the panel length (l) aligned along the array's width, the inter-panel spacing along the width (p1), the number of panels along the width (n1), and the impact of the PV array's tilt (θ). The tilt influences the projected ground footprint of the array.

  $$W = n1 * l * \cos(\theta) + (n1 - 1) * p2$$

- **Area footprint of a PV array (A):** This is derived from the calculated length (L) and width (W) of the PV array, incorporating the inter-row spacing (d) to account for the total land occupied by each array, and an additional percentage (s%) for necessary auxiliary components and infrastructure. The additional space is vital for ensuring operational access, safety, and integration of the entire electrical system.

  $$A = L\,(W + d)(1 + s\%)$$

- **Net area requirement per panel (Am):** This metric is calculated by dividing the area footprint of a single PV array (A) by the total number of PV panels within that array (n1×n2). This provides the effective land area required per panel, considering all spatial constraints.

  $$A_m = \frac{A}{n_1 n_2}$$

- **Total number of panels installable (N):** This is determined by dividing the total available project area by the net area requirement per panel (Am). This calculation provides the maximum number of panels that can be physically accommodated on the site.

$$N = \frac{Project\ Area}{Am}\text{, rounded off to nearest integral}$$

- **Ground Coverage Ratio (GCR):** The ratio of area under solar PV panel installation (excluding area for cabling, inverter, row space, right of way) to the total project area is defined as GCR83 . It is calculated considering the project area, the total number of panels installed (N), the panel dimensions (l and b), and the tilt angle (θ). The GCR is a critical parameter in AgriPV as it directly impacts the amount of sunlight reaching the crops and, consequently, agricultural productivity. A lower GCR generally allows for greater light penetration, which is often desirable for crop growth.

$$GCR = \frac{N \times l \times b \times \cos\theta}{Project\ Area}$$

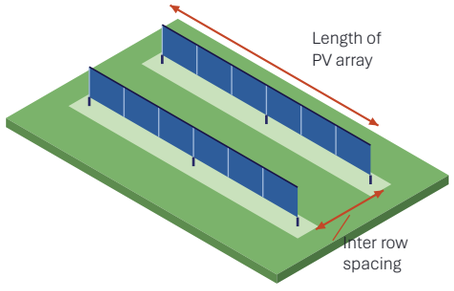
- DC capacity of the AgriPV project (Pdc): This is calculated by multiplying the total number of installable panels (N) by the rated capacity of each panel (C).

$$Pdc = N \times C$$

Vertical Oriented AgriPV system

For vertically oriented AgriPV systems, the PV array remains the smallest block layout of the system. The installable capacity within the project area is predominantly influenced by the inter-row spacing between arrays and the length of the PV array. Interpanel spacing within a vertical array is typically less critical and often not explicitly accounted for due to the nature of vertical mounting. The graphical representation of such system is shown in the Figure 38.

Figure 38: Illustration of vertical PV array layout



The parameters along with metrices which needs to be considered for capacity sizing based on design considerations pertaining to vertical setup are given in below table.

Table C3: Key metrices for capacity sizing based on design considerations – Vertical Oriented AgriPV system

Parameter	Metrices	Rationale
Panel length	"l' metres	Standard dimension of a single PV panel.
Panel breadth	"b" metres	Standard dimension of a single PV panel.
Inter row spacing between two PV arrays	"d" metres	Distance between consecutive vertical PV arrays. This is the primary determinant of agricultural space between arrays.
Number of panels in the PV array	"n" units	Total count of panels comprising a single vertical PV array.
Length of the PV array	"L" metres	Overall length of a single vertical PV array.

Table C3: (continued) Key metrices for capacity sizing based on design considerations – Vertical Oriented AgriPV system

Parameter	Metrices	Rationale
Additional space requirement	"s%"	Percentage of additional area required to accommodate ancillary infrastructure such as pathways, land topography variations, and the installation of critical electrical components including junction boxes, inverters, transformers, and battery storage systems. This factor is essential for practical deployment and operational efficiency.
Rated capacity of panel	"C" Watts	The nominal power output of a single PV panel under STC

From these parameters, the following calculations are performed to evaluate the system capacity:

- **Area footprint of a PV array (A):** This is calculated by considering the length of the PV array (L), the inter-row spacing (d), and the additional percentage (s%) required for balance-of-system components and operational access. The inter-row spacing is particularly important here as it defines the effective land utilization.

  $$A = L \times d \times (1 + s\%)$$

- **Net area requirement per panel (Am):** This is calculated by dividing the area footprint of a PV array (A) by the total number of PV panels in that array (n).

  $$Am = \frac{A}{n}$$

- Total number of panels installable (N): This is determined by dividing the total available project area by the net area requirement per panel (Am).

  $$N = \frac{Project\ Area}{Am}\text{, rounded off to nearest integral}$$

- **DC capacity of the AgriPV project (Pdc):** This is calculated by multiplying the total number of installable panels (N) by the rated capacity of each panel (C).

  $$Pdc = N \times C$$

The Ground Coverage Ratio (GCR) is typically not a primary calculation for vertical AgriPV projects. This is because the surface area onto ground of vertically mounted PV panels is often negligible.



Assessment Tools

Table C4: Assessment Tools for AgriPV site feasibility

Category	How to assess it (tools & methods)
Geotechnical & Topography	**Geotechnical Investigations and Soil Testing** – Subsurface conditions are assessed through geotechnical borings and test pits, followed by laboratory analysis to evaluate soil texture, compaction, shear strength, bearing capacity, and moisture retention. These parameters determine foundation stability for panel mounting systems and the rooting depth and productivity potential for crops under AgriPV layouts. **Ground-Penetrating Radar (GPR)** – GPR surveys are conducted to identify shallow bedrock, cavities, abandoned foundations, and subsurface heterogeneity that may constrain pile installation, drainage performance, or agricultural operations. **Topographic Surveys (LiDAR, DEM, GPS, Drones)** – High-resolution elevation models generated using LiDAR, GPS surveys, and drone imagery are used to assess slope gradients, erosion susceptibility, natural drainage paths, and machinery access. This informs site grading requirements, panel layout optimization, and erosion control strategies.
Hydrology	**Water Rights, Permits, and Regulatory Review** – Availability and reliability of water resources are assessed through a review of statutory water rights, permits, and allocations, supported by consultations with local authorities, irrigation boards, and landowners. This step establishes long-term legal feasibility for irrigated agriculture under the project. **Water Sampling and Quality Analysis** – Surface water and groundwater samples are collected from wells, canals, or storage facilities and analysed in laboratories for EC, pH, salinity, hardness, and metal content. Results inform irrigation suitability, crop selection, and potential risks to metallic structures and electrical equipment. **Drainage and Flood Risk Assessment** – Flood exposure and drainage performance are evaluated using watershed analysis, site topography, and publicly available floodplain datasets. Local drainage patterns and historic flood records are reviewed to identify inundation risks and define mitigation measures such as channel improvements or elevation adjustments.
Meteorology	**Solar Resource Assessment (Satellite and Ground Data)** – Long-term solar irradiance and climate datasets (e.g., satellite-derived and meteorological station data) are analysed to quantify site-specific solar availability and seasonal variability, forming the basis for energy yield estimation. **Energy Yield Modelling (PV Simulation Tools)** – Industry-standard PV modelling tools (e.g., PVsyst) are used to simulate system performance, incorporating irradiation data, panel tilt and spacing, shading losses, albedo effects from crop cover, and temperature-related losses to estimate expected generation. **Extreme Weather and Structural Load Assessment** – Wind, snow, hail, and temperature extremes are evaluated using local building codes (e.g., ASCE standards) and historical weather records to confirm structural integrity of mounting systems and assess climate-related risks to crops and equipment.



Table C4: (continued) Assessment Tools for AgriPV site feasibility

Category	How to assess it (tools & methods)
Agriculture	**Soil Fertility and Health Testing** – Laboratory soil testing is conducted to measure macronutrients (NPK), micronutrients, pH, salinity, organic matter, and soil texture. These results establish the baseline agricultural potential of the site and inform soil amendment and land management planning. **Field Walk-Throughs and Agronomic Surveys** – On-site inspections are carried out with agronomists or ecologists to assess existing crops, crop rotation practices, weeds, pollinators, soil cover, compaction, and visible stress factors. This qualitative assessment complements laboratory data and supports AgriPV compatibility analysis. **Baseline Productivity and Land-Use Review** – Historical land use and yield performance are reviewed to assess current productivity, identify constraints, and evaluate opportunities for improved land efficiency through combined agricultural and solar use.
Infrastructure	**Site Access and Logistics Assessment** – Access routes are evaluated through field surveys and road condition reviews to confirm suitability for construction equipment, material transport, and long-term operation and maintenance activities under panels. **Grid Interconnection and Electrical Infrastructure Review** – Grid proximity and connection feasibility are assessed through consultations with utilities, GIS-based mapping of substations and transmission lines, and review of available hosting capacity and interconnection requirements. **Constraints, Zoning, and Easements Analysis** – Physical and regulatory constraints are identified through GIS analysis, zoning and land-use reviews, utility searches, and environmental or right-of-way easement checks. This ensures compliance and identifies areas requiring design adjustments or exclusions.

C3. Assessment Methodology and Tools[83]

This table provides a detailed feasibility assessment for using different crops in AgriPV systems. It links each crop type to its scientific shade tolerance and then givesa practical recommendation on how well that crop might grow under solar panels, helping to identify the most suitable plants for dual-use land management.

83 **Disclaimer:** The information in this table is based on a synthesis of academic research and is intended for general guidance only; it is not a guarantee of crop performance. Actual results are highly dependent on site-specific conditions, crop variety, and AgriPV system design. Local pilot studies are strongly recommended before any large-scale implementation



Table C5: Feasibility Assessment of Crop Suitability for AgriPV Systems Based on Shade Tolerance

Crop Type	Assessment on Shade Tolerance[84]	Broad Inference on AgriPV Feasibility
Cereals	**Rice:** Generally, it requires full sun but can tolerate some shade in tropical regions (A), where it is often grown under partial canopy. Research suggests it may tolerate up to 30% RSR in shaded conditions.[85] **Wheat, Barley, Oats**: Shade-tolerant up to 50% RSR, with studies showing yield reductions of 13.1%–42.9% under pre-anthesis shading[86] and 38.6%–61.2% post-anthesis[87] , depending on cultivar. Shade tolerance in wheat is related to photosynthetic limitation and morphological and physiological adaptations. Shade stress can lead to decreased photosynthesis, but wheat can compensate through changes in leaf size, chlorophyll content, and other physiological processes to enhance light capture and energy conversion. **Maize:** Shade-susceptible; yield drops significantly from 1% RSR, with estimated yield loss at 40% RSR is 45%. **Sorghum, Millet:** C4 grasses[88] are typically sun-loving, but some varieties may tolerate moderate shade (up to 30% RSR) in dry climates (B), benefiting from reduced water stress.	**Rice**: Challenging due to water management under panels, but partial shade may reduce water loss in hot climates (A, Cfa), with potential for elevated panels to allow flooding for crop cultivation. **Wheat, barley, oats**: Feasible in hotter climates (e.g., Cfa, Dfa) where shade can reduce heat stress, but full sun is preferred, requiring careful panel design for light diffusion. **Maize**: Tall varieties may require high panels, but shade can help in hot regions (BSh, Cfa), with trade-offs between yield and energy production. **Sorghum, millet**: Benefit from shade in semi-arid zones (BSh) to reduce water stress, with AgriPV enhancing water conservation and reducing evaporation
Pulses/ Legumes	Generally, shade-susceptible grain legumes like soybeans, lentils, and chickpeas show yield declines even at low shading levels (1% RSR), with estimated yield loss of 50% at 40% RSR. Some leafy legumes (e.g., peas, beans) may tolerate moderate shade (up to 20% RSR).	Many legumes (e.g., lentils, chickpeas) are low-growing and can tolerate partial shade, making them suitable for AgriPV, especially in hot climates (A, BSh) where shade can reduce heat stress. Soybeans and peanuts may require lighter but could benefit from diffused shade, with potential for cultivation under elevated panels which can allow light penetration.
Oilseed Crops	**Soybean:** Shade-susceptible, like other legumes, requiring full sun for optimal oil production. **Sunflower, Rapeseed:** Sun-loving; shade-susceptible, with yield reduction under reduced light. **Sesame:** May tolerate moderate shade but generally prefers full sun, especially in dry climates. **Olives**: Perennial crops[89]; olives can tolerate some shade (up to 30% RSR), especially in Mediterranean climates (C), while palm oil may tolerate partial shade in tropical climate[90]	Olives and palm can be integrated into orchard-style AgriPV, with panels placed between trees, providing shade and reducing water loss in hot climates (A, B). Sunflower and rapeseed are taller and may require high panels, but partial shade can help in hot climates, with trade-offs for light intensity.

84 Most of the quantitative figures in the table are based on findings from a comprehensive global meta-analysis published in Agronomy for Sustainable Development (2022), titled "Contrasting yield responses at varying levels of shade suggest different suitability of crops for dual land-use systems" (https://link.springer.com/article/10.1007/s13593-022-00783-7), unless specified otherwise

85

86 Pre-anthesis shading in plants refers to reducing light exposure before the plant flowers and starts producing seeds

87 Post-anthesis shading in plants refers to reducing light exposure after the flowering stage (anthesis) and the development of seeds or grains.

88 C4 grasses are a group of plants, mainly in the grass family, that utilize a specialized photosynthetic pathway called the C4 pathway (also known as the Hatch-Slack pathway). This pathway allows them to efficiently capture and fix carbon dioxide, especially in warm and arid environments.

89 Perennial crops are plants that live for more than two years and do not need to be replanted each year.

90

Table C5: (continued) Feasibility Assessment of Crop Suitability for AgriPV Systems Based on Shade Tolerance

Crop Type	Assessment on Shade Tolerance	Broad Inference on AgriPV Feasibility
Root & tuber crops	Generally, shade-tolerant; can endure up to 40% RSR without significant yield loss. Cassava, yams, and taro are highly shade-tolerant, often grown under partial canopy in tropical regions, while potatoes and sweet potatoes tolerate moderate shade but prefer full sun.	Root crops grow underground but need light for photosynthesis. Partial shade may reduce soil temperature and water loss, especially in hot climates (A, B), with potential for cultivation under elevated panels.
Vegetable Crops	**Leafy Vegetables (e.g., Spinach, Cabbage):** Shade-tolerant; can endure up to 40% RSR, with studies showing minimal yield loss under partial shade. **Root Vegetables (e.g., Carrots, Onions):** Tolerate moderate shade (up to 30% RSR) but prefer full sun for optimal growth. **Fruiting Vegetables (e.g., Tomatoes, Peppers):** Shade-susceptible; require full sun for fruit set, with decline in yield under reduced light conditions	Leafy greens (e.g., spinach, cabbage) benefit from partial shade and microclimate control under panels, especially in hot climates (A, Cfa). Tomatoes and peppers may require lighter but can thrive with diffused shade, with potential for cultivation under elevated panels
Fruit Crops	**Berries (e.g., Blueberry, Blackberry):** Shade-benefiting; can tolerate up to 30-50% RSR **Bananas, Mangoes:** Tolerate moderate shade (up to 30% RSR), especially in tropical regions, often grown under partial canopy. **Apples, Grapes, Citrus:** Require full sun but some varieties may tolerate partial shade (up to 20% RSR), with reduction in yield under heavy shading	Tree fruits with lower heights (e.g., apples, citrus) and vines (e.g., grapes) can be integrated with panels in orchards or trellised systems, providing shade and reducing heat stress in hot climates (A, Cfa). Shade can reduce water loss and heat stress, with potential for cultivation in elevated panels to allow light penetration
Fiber Crops	Generally, shade-susceptible; requires full sun for optimal growth and fiber quality, with decline in yield under reduced light.	Cotton requires full sun, making it less suitable for AgriPV, with potential yield losses under panels. Hemp and flax may tolerate partial shade but typically need good light, with potential for AgriPV in warmer climates
Sugar Crops	**Sugarcane:** Shade-susceptible; requires full sun for optimal growth, with yield declines under reduced light. **Sugar Beet:** May tolerate some shade (up to 20% RSR) but prefers full sun, with potential yield reductions under heavy shading	Sugarcane is tall and requires full sun, making it less suitable for AgriPV, with potential yield losses under panels. Sugar beet may tolerate some shade but needs good light, with potential for AgriPV in shade-tolerant setup
Spice & Condiments	Many of the species are shade-tolerant; black pepper, turmeric, and ginger are often grown under partial canopy in tropical regions, enduring up to 40% RSR Chili and cumin prefer full sun but may tolerate moderate shade (up to 20% RSR)	Many spices (e.g., black pepper, turmeric) are shade-tolerant and can thrive under panels, making them highly suitable for AgriPV in tropical zones. Chili and cumin may require lighter but could benefit from diffused shade, with potential for elevated panels



Table C5: (continued) Feasibility Assessment of Crop Suitability for AgriPV Systems Based on Shade Tolerance

Crop Type	Assessment on Shade Tolerance	Broad Inference on AgriPV Feasibility
Beverage Crops	Highly shade-tolerant; traditionally grown under agroforestry systems with partial canopy cover, enduring up to 50% RSR.	Coffee and cocoa are traditionally shade-grown, making them highly suitable for AgriPV, with panels mimicking natural shade in tropical zones. Tea can also benefit from partial shade, with potential for AgriPV in temperate zone
Forage/ Fodder crops	Generally, shade-tolerant; can endure up to 25-50% RSR without significant yield loss, with forages like alfalfa and clover showing resilience under partial shade.[91]	Solar panels can provide shade for livestock and reduce water loss for forage crops, with grass and legumes growing well under panels in hot climates.
Medicinal & Aromatic Plants	Many of the species are shade-tolerant; mint and chamomile can thrive under partial shade (up to 40% RSR), while lavender prefers full sun but may tolerate 20% RSR[92]	Many of the medicinal crops (e.g., mint, chamomile) can tolerate partial shade and benefit from the microclimate under panels, especially in hot climates.

Research suggests that shade tolerance varies among crop categories, influenced by factors such as light saturation point (LSP)93 , light compensation point (LCP) 94 , and photosynthetic efficiency 95 under reduced light. It seems likely that shade-beneficial and shadetolerant crops, which can maintain or increase yieldsunder partial shade, are ideal for AgriPV, while sun-loving crops may experience yield losses. The evidence leans toward AgriPV being feasible in regions with abundant sunlight, like tropical and temperate zones, with some ambiguity over yield impacts in dry and continental zones due to water and temperature constraints.

91 91 Based on findings from a foundation paper published in Agroforestry Systems (1999), titled "Shade effects on forage crops with potential in temperate agroforestry practices (https://www.researchgate.net/publication/227138702_Shade_effects_on_forage_crops_with_potential_in_temperate_agroforestry_practices)

92 Based on findings from a research article published in International Journal of Environmental Health Research titled " Beyond the crop: the role of medicinal and aromatic plants in soil carbon sequestration and nitrogen cycling" (https://www.tandfonline.com/doi/full/10.1080/09603123.2026.2653197_)

93 The light saturation point refers to the level of light intensity where a plant's photosynthetic rate reaches its maximum capacity.

94 The light compensation point is the specific light intensity where a plant's rate of photosynthesis exactly matches its rate of respiration.

95 In the context of crop shade tolerance, understanding light saturation point, light compensation point, and photosynthetic efficiency is crucial. The light saturation point is the light intensity at which a plant's photosynthesis reaches its maximum rate; additional light beyond this point does not further enhance photosynthesis. Conversely, the light compensation point represents the minimum light intensity required for a plant to balance energy production through photosynthesis with energy consumption through respiration. Below this point, the plant experiences negative growth. Photosynthetic efficiency describes how effectively a plant converts light energy into chemical energy (sugars).

C4. Climate-Zone-Specific Crop Selection Considerations96

The relative importance of each crop selection criterion is not static; it shifts significantly based on the primary agricultural challenges and opportunities of a given climatic zone. Understanding this context is crucial formaking a realistic assessment. The following table converts the climate-wise crop-selection guidance into a consolidated matrix. Each row represents a cropselection parameter or risk area. The climate-zone columns explain how the parameter should be interpreted in that zone, while the final columns indicate the evidence to collect and the caution to apply before shortlisting crops.



Table C6: Climate-Zone Based Crop Selection Matrix: Parameters, Interpretations, and Evidence Requirements

Parameter / consideration	Nature of Parameter	Arid	Semi-arid	Tropical	Temperate	Continental	Site evidence to collect	Screening caution / decision implication
Benefit from microclimate: shade, cooling and stress reduction	*Common critical parameter*	Primary: Use panel shade to reduce heat stress, sunscald, bolting and excessive evaporation. Best suited to crops that benefit from moderated radiation rather than full shade.	Primary: Use shade to buffer dry-season heat, conserve soil moisture and support higher-value horticulture where open-field heat stress is limiting.	Primary: Relevant for understory or shade-adapted crops and heat-sensitive greens; also useful for extending harvest quality.	Primary: Useful for reducing summer heatwave stress, sunscald and bolting in leafy greens, berries and vegetables.	Primary: Useful during hot mid-summer periods but must be balanced with short growing season and lower-angle sunlight.	Crop shade tolerance, expected shade intensity, crop stage sensitivity, local heat-stress records, PV layout assumptions.	Do not assume shade is always beneficial. Excessive shade can reduce yield, especially for light-demanding and fruiting crops.
Water-use efficiency, drought mitigation and irrigation compatibility	*Common, strongest in dry zones*	Primary: Central parameter. Check water source reliability, salinity, drip/sub-surface drip suitability and crop water productivity.	Primary: Focus on conserving rainfall, bridging dry spells and using supplemental irrigation efficiently.	Site-specific: Less about water scarcity; more about drainage, humidity and waterlogging in many tropical sites.	Secondary: Useful for drought resilience and reducing supplemental irrigation during dry spells.	Secondary: Important for mid-season drought resilience and rainfall conservation.	Water source, irrigation method, crop water requirement, soil moisture, salinity, drainage, seasonal rainfall variability.	Water savings should not be assumed. Validate whether shade actually improves water productivity for the crop and site.
Mechanization / operational compatibility	*Common, especially mechanised zones*	Relevant: Prioritise row-planted vegetables/herbs compatible with drip irrigation and accessible small/medium equipment.	Relevant: Check compatibility with mixed farming, irrigation lines, livestock movement and seasonal field access.	Relevant: Labour access, harvesting pathways, humidity management and hand-harvest feasibility may dominate.	Secondary: Temperate farming is often mechanised; row spacing and column height must maintain efficiency.	Secondary: Continental farming often uses large equipment; system layout may need very wide spacing or a shift to smaller equipment.	Machinery dimensions, labour needs, access lanes, harvesting method, safety constraints, crop/O&M calendar.	If existing machinery cannot operate safely, the crop may require new equipment or smaller-scale production assumptions.

Table C6: (continued) Climate-Zone Based Crop Selection Matrix: Parameters, Interpretations, and Evidence Requirements

Parameter / consideration	Nature of Parameter	Arid	Semi-arid	Tropical	Temperate	Continental	Site evidence to collect	Screening caution / decision implication
Soil health improvement and erosion control	*Common but different drivers*	Secondary: Arid soils may be low in organic matter and vulnerable to degradation; rotations/legumes can help.	Secondary: Important for wind erosion and intense episodic rainfall; cover crops/legumes may improve resilience.	Secondary: Tropical soils may be acidic, nutrient-leached or erosion-prone; groundcovers and rotations can be important.	Secondary: Cover crops and living mulches can reduce erosion during heavy rain and support soil structure.	Secondary: Wind erosion control and continuous soil cover are important in open fields and fallow periods.	Soil type, organic matter, erosion history, slope, rainfall intensity, wind exposure, cover crop suitability.	Soil-health crops should still satisfy shade, water and operational fit; cover crops may compete with main crops if unmanaged.
Salinity tolerance	*Zone-specific*	Secondary: Often important due saline groundwater or salt accumulation in irrigated arid soils.	Site-specific: Relevant where irrigation water or soils are saline.	Site-specific: Usually not climate-wide; check coastal or irrigated pockets.	Site-specific: Assess only if local salinity risk exists.	Site-specific: Assess only if local salinity risk exists.	Soil EC, irrigation-water quality, salinity maps, farmer reports, crop tolerance thresholds.	Do not include as a high-weight parameter unless salinity is verified or likely at the specific site.
Fungal and disease resistance	*Zone-specific humid priority*	Lower priority unless irrigation/humidity creates disease pockets.	Site-specific where humidity or dense canopy occurs.	Secondary: Important because shade and reduced airflow may increase humidity and fungal pressure.	Site-specific during wet periods or dense canopy crops.	Site-specific in cool/wet periods.	Relative humidity, airflow, disease history, crop susceptibility, spacing, canopy density.	Do not recommend shade-loving crops without checking disease resistance and ventilation under panels.
Season extension and frost protection	*Zone-specific cool/cold priority*	Usually not a priority except high-elevation arid areas.	Usually not a priority except frost-prone localities.	Usually not a priority except upland tropical/subtropical frost pockets.	Primary: Can support early/late-season production and protect frost-sensitive crops.	Primary: Short growing season makes frost buffering and timing critical.	Frost dates, crop calendar, temperature records, panel height, ground heat retention, cultivar duration.	Season extension should be validated locally; panel effects may be modest and vary by layout and weather.

Table C6: (continued) Climate-Zone Based Crop Selection Matrix: Parameters, Interpretations, and Evidence Requirements

Parameter / consideration	Nature of Parameter	Arid	Semi-arid	Tropical	Temperate	Continental	Site evidence to collect	Screening caution / decision implication
Protection from weather damage: hail, storms and intense rain	*Zone-specific storm/cold priority*	Secondary through soil-health lens; relevant during intense storm events.	Secondary: Important during sporadic intense rainfall and erosion events.	Primary: Panel canopy can reduce direct rain impact, soil compaction, runoff and nutrient loss in intense rainfall.	Primary: Protects high-value delicate crops from hail and intense rain.	Primary: Hail and summer storms can be key risks for diversified horticulture.	Hail/storm frequency, crop damage history, insurance/loss data, structural design assumptions.	Weather protection benefits must be compared against added cost and structural load requirements.
Wind and soil erosion control	*Zone-specific open-field priority*	Can be relevant in desert margins and exposed soils.	Relevant where wind erosion is observed in dry seasons.	Site-specific; less dominant where vegetation cover is high.	Site-specific in exposed fields.	Secondary: Important in vast open fields, fallow periods and topsoil-loss contexts.	Wind speed, exposed field length, soil texture, fallow periods, cover crop plan, topsoil loss history.	Windbreak effects depend on layout and may not protect all parts of the field equally.
Dynamic light management / bifacial and snow synergy	*System-design parameter, zone-specific*	Not typical as a crop-selection driver.	Not typical as a crop-selection driver.	Not typical as a crop-selection driver.	Potentially relevant where seasonal light management matters.	Specific: Tracking, bifacial panels, snow shedding and frost-line foundations may influence crop timing and crop choice.	Seasonal sun angles, snow cover, crop calendar, tracker strategy, structural snow-load requirements.	This is not a crop parameter by itself; it informs whether the proposed PV design can support the crop calendar.

C5. Business models description[97]

Farmer-Owned Model

In the farmer-owned model, the farmer or landowner retains complete ownership and operational control over the AgriPV system. This includes both agricultural activities and solar power generation. The farmer is responsible for the initial investment, which can be financed through a combination of personal equity, loans from financial institutions, government schemes, or private investors.

Key responsibilities for the farmer include the planning, procurement, and installation of the solar PV system, as well as its ongoing operation and maintenance. The farmer also manages all aspects of crop cultivation, from planting and irrigation to harvesting and sales.

All revenue generated from the sale of electricity to distribution companies (Discoms) and from the sale of agricultural produce accrues to the farmer. While this model offers the potential for diversified income and energy independence, it also presents challenges such as the need for substantial upfront capital and the technical expertise required to manage both agricultural and energy-generating operations.

FPO / Community-Owned Model

Under the FPO or community-owned model, a Farmer Producer Organization (FPO), cooperative, or community entity develops, owns, and manages the AgriPV installation on behalf of participating farmers.

Multiple farmers contribute land and collectively share investment costs, risks, and revenues. The FPO oversees project financing, procurement, operations, and maintenance, while farmers participate in agricultural activities on the land. Income generated from electricity sales and agricultural production is distributed among members based on agreed sharing mechanisms. This model improves accessibility for small and marginal farmers by reducing individual financial burdens and leveraging economies of scale.

Developer-Owned Model

Under the developer-owned model, a third-party developer (entity/person other than the farmer) finances, owns, and operates the solar installation on land leased from a farmer. The farmer continues to own the land and carry out agricultural activities, while receiving regular lease payments from the developer for the use of the land.

The primary role of the developer is to manage the entire lifecycle of the solar project, including site assessment, system design, financing, installation, and maintenance. The developer assumes the financial and operational risks associated with the solar energy generation component of the project. Revenue from the sale of electricity to Discoms or other buyers belongs to the developer.

The farmer, in turn, focuses on agricultural production, adapting their practices to the presence of the solar infrastructure. This model provides farmers with a stable, additional income stream from land lease payments, reducing their financial risk and dependence on agricultural yields alone.



Joint Ownership Models

Joint ownership models involve hybrid structures with shared ownership and responsibilities between multiple stakeholders such as developers and farmers

- **Discom and Farmer Owned:** In this model, a distribution company (Discom) and a farmer enter into a partnership to develop and operate an AgriPV project. Discom may take the lead in financing and managing solar installation, while the farmer provides the land and continues to manage agricultural activities. Ownership of the AgriPV system is shared, and revenues from electricity and crop sales are distributed according to a pre-agreed arrangement. This model can facilitate grid integration and improve power quality, particularly in remote areas. The farmer benefits from a reduced financial burden and technical support from the Discom, while the Discom gains access to land for renewable energy generation.
- **Developer and Farmer Owned:** This model represents a joint venture where a solar developer and a landowner share ownership of the AgriPV project. Both parties contribute to the project's capital investment and share the profits from both electricity and agricultural sales. This collaborative approach allows for the pooling of resources and expertise, with the developer bringing technical and financial know-how and the farmer providing land and agricultural knowledge. Shared ownership can help to align the interests of both parties, fostering a more integrated and synergistic approach to managing the dual-use system.

Open Access Model

Under the open access model, a developer or investor installs and operates the AgriPV system on leased agricultural land, while the generated electricity is sold directly to commercial and industrial consumers through open access arrangements rather than to Discoms. Farmers continue cultivating crops and receive lease payments for land use.

The project developer is responsible for financing, operating, and managing solar installation, while also securing long-term power purchase agreements with corporate buyers. By accessing a broader market of consumers, this model can achieve higher power tariffs and improved project economics. However, project viability is influenced by regulatory frameworks, transmission charges, and state-specific open access policies.

FMCG-Integrated Model

Under the FMCG-integrated model, an AgriPV project serves as a dual supplier of renewable electricity and agricultural produce to Fast-Moving Consumer Goods (FMCG) companies. The solar component is typically owned and operated by a developer or project entity, while farmers continue agricultural production under contractual arrangements.

In addition to purchasing renewable electricity, FMCG companies procure agricultural produce directly from participating farmers, creating an integrated and traceable supply chain. This model enhances market access, reduces intermediary costs, and provides farmers with more secure demand for their produce. It also supports corporate sustainability objectives by linking renewable energy procurement with responsible agricultural sourcing.



Value-Addition Model

Under the value-addition model, electricity generated from the AgriPV system is used to power agricultural infrastructure such as cold storage facilities, food processing units, pack houses, flour mills, or irrigation systems. The AgriPV asset may be owned by farmers, FPOs, or community organizations depending on the project structure.

Beyond generating electricity and agricultural output, the model creates additional value by enabling on-site processing, storage, and preservation of farm produce. This helps reduce post-harvest losses, improve product quality, and increase farmer realization through access to higher-value markets. As a result, the model expands AgriPV from a dual-use system into a broader rural development and value-chain enhancement platform.

Clean Fuel Integration Model

Under the clean fuel integration model, electricity generated from AgriPV systems is utilised to produce renewable fuels such as green hydrogen, biogas, bioCNG, or biofuels. The project is typically owned and operated by an energy developer or specialized cleanenergy company, while agricultural activities continue the same land.

The AgriPV installation functions as a renewable energy hub, supplying power for fuel production while preserving agricultural productivity. Farmers continue to earn income from crop cultivation and may also benefit from supplying agricultural residues or biomass feedstock where relevant. By creating multiple energyproducts from a single site, this model enhances revenue diversification and supports broader decarbonisation objectives within the agriculture and energy sectors

Revenue Sharing Models

Revenue sharing models are agreements that focus on the distribution of income from the AgriPV project, rather than on the ownership of the assets. These models can be structured in various ways to suit the specific needs and contributions of the stakeholders involved.

- **Royalty Model:** In a royalty-based model, the farmer or landowner receives a regular payment, or royalty, from the developer who owns and operates the solar installation. This royalty is typically calculated as a percentage of the revenue generated from electricity sales or as a fixed amount per unit of land used for the solar panels. This model provides the farmer with a predictable income stream that is directly linked to the performance of the solar project, without the need for any upfront investment.
- **Profit-Sharing Agreement:** Under a profit-sharing agreement, the farmer and the developer, or other stakeholders, agree to share the net profits generated by the combined AgriPV operation. This model requires a transparent and mutually agreed-upon method for calculating profits, considering all revenues and costs associated with both energy generation and agricultural production. Profit-sharing can motivate all parties to work towards maximizing the overall productivity and profitability of the AgriPV system.



Land Sharing Model

The Land Sharing Model enables farmers to lease a portion or the entirety of their agricultural land to a developer for the installation of agriphotovoltaic (Agri-PV) infrastructure while continuing cultivation activities beneath or around the solar installations. This arrangement allows for simultaneous agricultural production and renewable energy generation, maximizing land-use efficiency and providing farmers with income from both farming operations and land lease or electricity revenue-sharing agreements.

Joint Venture Model

The Joint Venture Model is a collaborative arrangement between farmers and developers in which both parties contribute resources toward the Agri-PV project. Farmers typically provide land, while developers contribute capital, technology, and operational expertise. Revenues generated from agricultural production and solar electricity generation are shared according to a mutually agreed profit-sharing mechanism, aligning the interests of both stakeholders.

CSR-Funded Model

Under the CSR-Funded Model, private companies utilize Corporate Social Responsibility (CSR) funds to finance the installation of Agri-PV systems on agricultural land.

Farmers retain ownership and cultivation rights over their land while benefiting from improved infrastructure, access to renewable energy, and enhanced agricultural productivity. This model promotes rural development and sustainable farming practices without requiring significant upfront investment from farmers.

Lease-Based Model

The Lease-Based Model involves farmers leasing their land to a developer for the establishment and operation of an Agri-PV system. The developer assumes responsibility for project financing, construction, operation, and maintenance, while farmers receive predetermined lease payments and continue agricultural activities where feasible. This model offers a stable and low-risk income stream for farmers with limited investment requirements.

Power Purchase Agreement (PPA)-Based Model

In the PPA-Based Model, a developer installs and operates an Agri-PV system and enters into a long-term Power Purchase Agreement (PPA) with a utility, commercial consumer, or other off-taker for the sale of electricity. The predictable revenue generated from the agreement improves project bankability and attracts private investment. Farmers may benefit through lease payments, revenue-sharing arrangements, and continued agricultural production on the project site.

Government Utility-Backed Model

The Government Utility-Backed Model relies on financial and policy support from government agencies or public utilities to facilitate Agri-PV deployment. Support mechanisms may include capital subsidies, grants, taxincentives, concessional financing, or guaranteed power procurement arrangements. Projects may be established on public or privately owned land, while farmers continue cultivating crops under a supportive regulatory framework. This model enhances project viability and accelerates the adoption of agriphotovoltaics at scale

Appendix D – Worked Methodology Demonstrations

To demonstrate the AgriPV system design approach, an illustrative location and corresponding weather dataset have been selected for simulation and analysis purposes. The selected location is intended solely to showcase the methodology, design considerations, and system-sizing approach adopted in this study. Actual AgriPV system design should be undertaken using sitespecific meteorological, geographical, agricultural, and techno-economic parameters.

It should be noted that climatic conditions can vary significantly across project locations, and certain regions may exhibit transitional characteristics between multiple climate classifications rather than fitting within a single Köppen climate category. Consequently, system configuration, crop selection, structural design, spacing requirements, and energy yield may di er from the illustrative example presented. The results should therefore be interpreted as indicative and adapted to local conditions during project-specific planning and detailed design.

D1. Illustrative AgriPV system designing: Arid Zone — Minya Governorate, Upper Egypt

Executive Summary

This study applies the project's own crop-selection methodology — the four-step selection process and the crop suitability matrix — to a specific 4.0-hectare parcel in Minya Governorate, Upper Egypt. The objective is to shortlist the crops best suited to be grown beneath an AgriPV array at this location, given its hyper-arid climate, complete dependence on Nile irrigation, smallholder farming structure, and export-oriented market context.

Figure 39: Arid zone illustrative site highlighted over map



Following the framework strictly, a longlist of crops currently grown in the region was compiled, screened through the non-negotiable technical prerequisites (shade tolerance and low-to-medium height), and the survivors were scored against eight weighted parameters. The weightings were re-calibrated from the illustrative defaults to reflect this site's binding constraints — water scarcity and extreme heat — and itseconomic reality, where per-unit market value drives smallholder income and national foreign-currency priorities.

Result. The highest-scoring, most suitable crops for AgriPV at this site are **medicinal & aromatic plants (MAPs) and garlic, followed by leafy greens and a closely grouped tier of onion, tomato and potato**. These crops combine strong benefit from panel shade (heat and dust-storm protection, reduced evapotranspiration) with high market value per unit ofland and per unit of increasingly scarce water — the combination that matters most at this location.

Site Context and Key Constraints

The parcel is a rectangular 200 m × 227 m plot (≈ 4.54 ha) at 28.0822°N, 30.7100°E, on the west-bank agricultural strip of the Nile Valley. The site's defining characteristics, taken from the supplied site brief, are summarised below.

Table D1: Illustrative Site Details for Arid Zone — Minya Governorate, Upper Egypt

Parameter	Detail
Climatic zone	Arid
Temperature	Annual mean ~22 °C. Summer (Jun–Aug) 35–42 °C daily max, 20–24 °C min; Winter (Dec–Feb) 18–24 °C max, 5–9 °C min.
Precipitation	Extremely low — < 25 mm/year; effectively zero reliable rainfall.
Irrigation	100% irrigated — Nile-fed canal system (flood/furrow traditional, transitioning to drip/sprinkler on modern farms).
Soil type & texture	Nile alluvial Fluvisols / Entisols; deep and fertile, calcareous on western margins. Silty clay to clay loam in older floodplain; sandy loam to loamy sand on reclaimed desert margins.
Organic matter	Low (0.5–1.5%) due to intense mineralisation under high temperatures.
Growing seasons	Three overlapping seasons — Winter (Oct–Feb), Summer (Mar–Jun), Nili (Jul–Sep) — enabling 2–3 crop cycles per year.
Farming system	Smallholder-dominated (0.5–3 feddan typical), canal-irrigated, labour-intensive; government-regulated cropping areas for staples.
Key risks	Extreme heat stress, water scarcity, soil salinisation, sand/dust storms (Khamsin) assessed as very high.

What the site tells us about priorities

- **Water** is the single binding constraint: with negligible rainfall and 100% reliance on a quota-limited Nile canal supply under mounting national water stress, any crop's water demand — and its ability to convert panel shade into real irrigation savings — is decisive.
- **Heat and dust** are the primary agronomic hazards: summer maxima of 35–42 °C and recurrent Khamsin dust storms are exactly the stresses that an overhead PV array mitigates, so the crops that gain most from that protection are strongly favoured.
- Economic context is **smallholder and exportoriented: plots are small and labour is abundant and inexpensive**, so heavy mechanisation matters little, while high market value per feddan — ideally export-grade and foreign-currency-earning — matters greatly.

Methodology

The analysis follows the project's four-step cropselection process:

Table D2: Crop Selection Parameters and Process for Arid Zone — Minya Governorate, Upper Egypt

Stage	What is done
1. Initial Longlist	Compile all crops currently cultivated or known to be suitable for the local climate, without yet considering AgriPV constraints.
2.Technical Prerequisites Filter (Go/No-Go)	Screen every crop against two non-negotiable requirements — high shade tolerance and low-to-medium height/growth stature. Sun-loving and tall crops are removed, as they would be shaded out or would physically shade / damage the panels.
3. Prioritization Matrix	Score each surviving crop from 1 (very poor fit) to 5 (excellent fit) against eight weighted parameters spanning technical and economic considerations, using site-specific weightings. Weighted score = raw score × weightage (in percentage points), exactly as in Table 5.
4. Final Selection	Rank crops by total weighted score; the highest scorers form the recommended shortlist.

Step 1 — Initial Longlist: Drawing on regional agricultural profiles for Minya and Upper Egypt (governorate crop statistics, FAO/IFAD project records, and Egyptian export data), the crops currently grown or established in the area were compiled. Minya is Egypt's leading wheat producer and a major producer ofsugarcane, cotton and onions, with an established base in vegetables, legumes, fodder and — increasingly — high-value medicinal and aromatic plants supported by a smallholder development programme in the governorate.

Table D3: Long List of Crops considered for Arid Zone — Minya Governorate, Upper Egypt

Group	Crops on the longlist
Cereals / staples	Wheat, maize (corn), sorghum/millet
Industrial / cash	Sugarcane, cotton, sugar beet
Legumes & fodder	Broad (fava) beans, soybean, berseem (Egyptian clover, fodder)
Alliums	Garlic, onion
Vegetables	Tomato, potato, peppers, leafy greens (spinach, lettuce), watermelon
Fruit / perennial	Grapes, dates
High-value non-traditional	Medicinal & aromatic plants — basil, chamomile, mint, cumin, coriander, fennel, marjoram

Step 2 — Technical Prerequisites Filter (Go / No-Go): Each longlisted crop is screened against the two nonnegotiable prerequisites. A crop must have high shadetolerance (AgriPV arrays typically cut photosynthetically active radiation by 30–50%) and a low-to-medium height so it neither out-grows the under-panel clearance norshades or damages the modules. Tall C4 and sundemanding crops are eliminated at this stage regardless of their local importance.

Table D4: Crops screening framework for Arid Zone — Minya Governorate, Upper Egypt

Crop	Shade tolerance	Height / stature	Verdict	Rationale
Sugarcane	Low	Very tall (2–4 m)	**No-Go**	Tall, sun-loving C4; physically incompatible with panels.
Maize (corn)	Low	Tall (2–3 m)	**No-Go**	Sun-loving C4; height conflicts with array clearance.
Cotton	Low	Medium-tall	**No-Go**	Sun-demanding; yield falls sharply under heavy shade.
Wheat	Low–Med	Medium	**No-Go**	Full-sun staple; also, government-regulated cropping, so not freely selectable.
Dates (palm)	n/a	Very tall	**No-Go**	Palms tower above any array; incompatible.
Grapes	Low–Med	Tall / trellised, perennial	**No-Go**	Sun-loving, trellised and permanent; conflicts with panel geometry and rotation.
Watermelon	Low	Sprawling, sun-loving	**No-Go**	Fruiting cucurbit needs high light for fruit set; poor under dense shade.
Soybean	Low–Med	Medium	**No-Go**	Sun-loving grain legume; limited shade tolerance.
Medicinal & aromatic plants	High	Low	**Go**	Many species gain essential-oil content under partial shade; low stature.
Garlic	Med–High	Low	**Go**	Cool-season allium; low, tolerates and benefits from reduced heat.
Onion	Med	Low	**Go**	Low allium; established shade tolerance in AgriPV trials.
Leafy greens (spinach, lettuce)	High	Low	**Go**	The classic AgriPV 'champion' group; shade reduces bolting and heat stress.
Potato	Med	Low	**Go**	Cool-season root crop; tubers benefit from cooler, moister soil.
Tomato	Med	Medium	**Go**	Conditional: benefits from heat/VPD relief and higher water-use e iciency at moderate shade (25–50% GCR).
Peppers	Med–High	Low-medium	**Go**	Tolerate 35–50% PAR reduction; heat protection improves fruit quality.
Sugar beet	Med	Low	**Go**	Root crop, low canopy; moderate shade tolerance.
Broad (fava) beans	Med	Medium	**Go**	Cool-season legume; conditional, good rotation value.
Berseem (Egyptian clover)	Med–High	Low	**Go**	Shade-tolerant fodder legume; useful rotation/intercrop and fixes nitrogen.

Outcome of the filter: The technically feasible set carried into scoring is **medicinal & aromatic plants, garlic, onion, leafy greens, potato, tomato, peppers, sugar beet, broad beans and berseem**. To keep the prioritization matrix decision-focused, six finalists that best represent the feasible economic and agronomic spread were carried into full scoring: medicinal & aromatic plants, garlic, onion, leafy greens, tomato and potato. Peppers track closely with tomato; sugar beet, broad beans and berseem remain strong secondary/ rotation options

Step 3 — Prioritization Matrix

Weighting rationale: The framework explicitly instructs users to adjust the weightage column to match the project's goals. The weightings below are re-calibrated to this site's binding constraints. The main changes from the illustrative defaults are **water & irrigation needs raised from 15% to 25% (water is the decisive scarcity at this site); Ease of Mechanization cut from 15% to 5% (smallholder plots with abundant, low-cost labour gain little from mechanisation); and Level of Demand / Value kept high at 25% (per-unit area value and export/foreign-currency potential drive smallholder livelihoods)**. Weights sum to 100%.

Table D5: Customized Weighting Rationale for Crop Selection Based on Site-Specific Constraints for Arid Zone — Minya Governorate, Upper Egypt

Parameter	Weight	Rationale (site-specific)
Resilience to Climate Change	**20%**	Heat stress and Khamsin dust storms are top-rated risks; panel protection is the core value proposition here, so this stays high.
Ease of Mechanization	**5%**	Reduced from 15%. Smallholder plots with abundant, inexpensive labour make mechanisation a minor consideration.
Water & Irrigation Needs	**25%**	Raised from 15%. With < 25 mm rain and 100% quota-limited Nile irrigation, low water demand and shade-driven water savings are the single most important technical factor.
Crop Rotation & Intercropping	**5%**	Low soil organic matter (0.5–1.5%) and salinisation risk make rotation and legume intercropping valuable, but secondary to water and value.
Labour Intensity	**5%**	Labour is abundant; high labour need is only a mild negative and even supports rural employment, so weighted low.
Lifespan of the Crop	**5%**	Three overlapping seasons allow 2–3 cycles/year; short annuals that fit multi-cropping are mildly preferred.
Level of Demand (Value)	**25%**	High per-unit / export value is the primary route to smallholder income and national foreign-currency goals; kept at the top weight.
Area Under Cultivation	**10%**	Existing regional scale signals established markets, agronomic know-how and input supply — helpful for adoption, hence a moderate weight.
Total	**100%**	

Scoring (1 = very poor fit … 5 = excellent fit): Each finalist is scored against every parameter on the 1–5 scale, based on the external research.

Prioritization Matrix (scoring): Scores 1–5. The bottom row shows the total weighted score (Σ score × weight), directly comparable to the illustrative Table 5 total of 420.

Table D6: Crop prioritization scoring matrix for Arid Zone — Minya Governorate, Upper Egypt

Parameter	Wt %	MAPs	Garlic	Onion	Leafy greens	Tomato	Potato
Resilience to Climate Change	20	5	4	4	5	4	4
Ease of Mechanization	5	2	2	3	3	3	4
Water & Irrigation Needs	25	4	4	3	5	3	3
Crop Rotation & Intercropping	5	3	4	3	4	3	2
Labour Intensity	5	2	2	2	3	2	4
Lifespan of the Crop	5	4	4	4	5	4	4
Level of Demand (Value)	25	5	5	4	2	4	4
Area Under Cultivation	10	3	4	5	3	5	4
Total Weighted Score	100	410	405	365	380	365	365

Step 4 — Final Selection and Ranked Shortlist

Ranking the six finalists by total weighted score gives the recommended shortlist below. Two crops lead clearly; leafy greens place third on technical merit despite lowmarket value; and onion, tomato and potato form a solid, closely tied secondary tier.

Table D7: Final list of crops shortlisted for Arid Zone — Minya Governorate, Upper Egypt

Rank	Crop	Score /500	Why
1	Medicinal & Aromatic Plants[98]	410	Best all-round fit: shade lifts essential-oil content, strong heat/dust protection, modest water use, and the highest market value with an established Minya smallholder export programme.
2	Garlic	405	High-value export allium (Egypt is a top 4 global producer); low stature, benefits from cooler microclimate, good rotation value. Labour-intensive but that suits the local workforce.
3	Leafy greens (spinach, lettuce)	380	The strongest technical fit — highest shade tolerance and water savings, very short cycles for multi-cropping — but low per-unit value and perishability cap its score.
4	Onion	365	Established, large-area export crop with excellent regional know-how; slightly higher water need and lower unit value than garlic.

98 Medicinal and aromatic plants should be assessed at species and cultivar level. Partial shade may improve biomass, essential-oil concentration, selected quality attributes, or heat-stress tolerance in some species, but these responses are not uniform. Biomass yield, oil concentration, total oil yield per unit area, and oil composition should therefore be evaluated separately before commercial-scale selection.

Table D7: (continued) Final list of crops shortlisted for Arid Zone — Minya Governorate, Upper Egypt

Rank	Crop	Score /500	Why
4	**Tomato**	365	High demand and strong water-use-e iciency gains under moderate shade; needs careful array density (25–50% GCR) to protect fruit set.
4	**Potato**	365	Major export vegetable, most mechanisable and least labour-intensive of the set; rotation/disease management and moderate water need hold it level with onion and tomato.

Recommended primary shortlist: medicinal & aromatic plants and garlic, with leafy greens as a fastcycle intercrop and onion / tomato / potato as proven rotation partners. This combination maximises value earned per drop of Nile water while exploiting exactly the heat- and dust-protection that the array provides.

Crop Recommendations by AgriPV Configuration

The ranking in Steps 1–4 assumes an elevated (overhead) array — the most common AgriPV form, where crops grow directly beneath the panels under partial shade. But the physical structure of the system dictates the light and microclimate the crop receives, so the best-fit crop set changes with the configuration. The three configurations of interest are compared below and then discussed in turn, tailored to this Minya site.

Table D8: Comparison of Crop Suitability Across AgriPV System Configurations for Arid Zone — Minya Governorate, Upper Egypt

Configuration	Light / shade regime	Recommended crops (this site)	Key rationale
Elevated (overhead)	Moderate–high partial shade beneath panels (≈ 25–50% ground-coverage ratio).	**MAPs, garlic, leafy greens, onion, potato; tomato & pepper at lower panel density.**	Matches the Step 3 matrix ranking. Shade-tolerant, high-value crops convert heat/dust protection and reduced evapotranspiration into real water savings.
Vertical (bifacial, E/W-facing)	Near-full sun in wide inter-row strips; brief morning & evening shade bands.	**Wheat & cereals, berseem & fodder legumes, sugar beet, broad (fava) beans, onion, potato.**	Inter-row strips receive almost full light, so sun-loving staples excluded by the overhead filter become viable again. E/W verticals shed dust well (resisting Khamsin soiling) and leave the field fully machine workable.
Polyhouse (semi-transparent roof PV, ~25% cover ratio)	Controlled climate; ~25– 40% PAR reduction with stabilised midday temperature.	**Tomato, cucumber, sweet pepper, strawberry, premium leafy greens & herbs, seedlings/nursery, cut flowers.**	Protected, o -season and export-grade horticulture. In a high-light arid climate the roof PV curbs midday heat and photoinhibition; a ~25% cover ratio keeps even high-light crops within a small yield penalty. Highest value and water-use e iciency, but highest capital cost.

Elevated (overhead) AgriPV — primary recommendation

- Panels are mounted 3-3.5 m above ground on posts or cables so machinery can pass underneath, and crops grow directly beneath in a uniform partial shade. This is the configuration the Step 3 matrix was built around, so its recommendation is the ranked shortlist from Step 4: medicinal & aromatic plants and garlic as primary crops, leafy greens as a fastcycle intercrop, and onion, tomato and potato as proven rotation partners. These crops either tolerate or actively benefit from 30–50% light reduction, and at this hot, water-scarce site the shade delivers its greatest value — lower canopy temperature, reduced evapotranspiration and protection from dust and sunscald. Fruiting crops (tomato, pepper) should sit in lower-density rows (≈ 25–50% ground-coverage ratio) so fruit set is not light-limited. This configuration is the best match for small, high-value plots and is the recommended default for the site.

Vertical (bifacial) AgriPV

- Bifacial panels are mounted vertically in rows (typically east/west-facing) — occupying only a few centimetres of ground each, with wide (roughly 8–12 m) crop strips between rows. The cropped strips receive close to full sunlight for most of the day, interrupted only by short shade bands in the morning and late afternoon. This flips the crop logic: crops that failed the overhead shade filter because they are sun-loving now become suitable. For this site that reopens the region's staple and field crops — wheat and other cereals, berseem (Egyptian clover) and other fodder legumes, sugar beet, and broad (fava) beans — alongside onion and potato; field trials have even sustained maize and cereals with no significant yield loss between vertical rows.
- Two features make this configuration especially attractive at Minya. First, east/west vertical panels are highly resistant to dust soiling — rain and gravity clear them and there is no flat surface for dust to settle — which directly counters the site's recurrent Khamsin dust storms that would otherwise foul tilted panels and cut both energy and crop light. Second, the near-continuous open strips keep the land fully workable by machinery and compatible with the government-regulated staple cropping that dominates the area. The trade-off is that the crop receives less of the heat- and water-saving shade benefit than under an overhead array, so vertical systems are the right choice where the goal is to keep producing staples and fodder while adding solar energy with almost no loss of cultivable land, rather than maximise per-drop water savings.

Polyhouse / greenhouse-integrated AgriPV

- Here semi-transparent PV modules are integrated into the roof of a protected greenhouse (polyhouse), typically at a PV cover ratio of about 25%, so the crop grows in a controlled environment beneath partial roof shading. Research in hot, high-light arid climates shows that at ~25% cover ratio even light-demanding crops keep their yield within a small penalty, while the roof PV stabilizes midday canopy temperature and prevents photoinhibition — a real agronomic gain under Minya's 35–42 °C summers. The controlled environment also gives the highest wateruse e iciency (drip or hydroponic) and enables o season and export-grade production.
- The best-fit crops here are high-value protected horticulture: tomato, cucumber and sweet pepper (which do well at ~25% cover ratio), strawberries, premium leafy greens and herbs, plus nursery/seedling production and cut flowers. This configuration delivers the highest value per square metre and the tightest water control, but also the highest capital cost and a cooling requirement, so it suits modern or reclaimed-margin farms, grower cooperatives or contract-export operations rather than the smallest smallholders. For a high-value species such as an aromatic herb grown for export, a polyhouse can combine protected-cropping quality with on-site energy.

Crop-Specific Rationale and Implementation Notes

- **Medicinal & aromatic plants (top pick):** Species such as basil, chamomile, mint, marjoram and cumin are already grown by Minya smallholders under a national development programme, and Egypt is a leading global MAP exporter. Partial shade is not merely tolerated — for many aromatic species it raises essential-oil concentration and quality while reducing heat and water stress, so the panels add value rather than subtract it. High price per unit area and foreign-currency earnings make this the strongest economic fit; the main watch-points are crop-specific shade optima, post-harvest drying/handling quality, and matching species to buyer contracts.
- **Garlic (top pick):** A cool-season, low-stature allium with a large and growing export market. It benefits from the cooler under-panel microclimate, has good rotational and mild pest-suppressive properties, and stores and dehydrates well — the dried-garlic value chain is a major Egyptian industry. It is labourintensive, which is a poor fit only where labour is scarce; here it is an asset. Pair with drip irrigation and mulch to convert shade into measurable water savings.
- **Supporting crops:** Leafy greens give quick, shadeloving catch crops between main-season plantings and are ideal for the highest-shade zones directly beneath modules. Onion, tomato and potato are proven, market-ready rotation partners; tomato and peppers should sit in moderate-shade rows (25– 50% ground-coverage ratio) so fruit set is not lightlimited. Berseem clover and broad beans are valuable nitrogen-fixing rotation/intercrops that address the site's low organic matter and help manage salinity.

System design pointers for this site

- Target a **moderate ground-coverage ratio (≈ 25–50%)** so leafy/aromatic crops get water-saving shade while fruiting crops retain enough light.
- **Prioritise drip/sub-surface** irrigation to capture the shade-driven evapotranspiration savings that justify AgriPV in drylands (documented by ICARDA's MENA trials).
- Use **panel rows as wind/dust breaks and design for easy cleaning after Khamsin events**, since dust cuts both PV output and crop light.
- **Exploit the 2–3 season calendar:** winter alliums/aromatics, shoulder-season leafy greens, and heat-tolerant fruiting vegetables in the hottest window when shade helps most.
- **Manage salinity actively (leaching fraction, gypsum on calcareous margins)** and build organic matter with legume rotations, given the low baseline OM.

Limitations: This is a desk study using an illustrative parcel; scores are expert judgements on a 1–5 scale and are inherently approximate. Real deployment should confirm the Nile water allocation and any government cropping restrictions for the plot, run a one-to-twoseason on-site trial (crop response to shade is site- and cultivar-specific and varies year to year), secure buyer/export contracts before committing to MAPs or garlic at scale, and finalise array geometry with a coupled energy-yield and agronomy model. Weightings can and should be revisited with the project owner if priorities (e.g., maximising employment vs. maximising value) di er from those inferred here.

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Solar PV System Design Basis and Structural Assumptions

All PV energy yield simulations presented in this study are based on a uniform AgriPV structural and electrical configuration, applied consistently across all evaluated climatic zones (arid, semi-arid, tropical, continental,and temperate). This approach ensures that observed performance variations are attributable primarily to climate and irradiation characteristics, rather than design inconsistencies.

The standard structural parameters adopted for simulation are summarized and disclosed in the Technical Annex.

Table D9: Standard Structural Parameters Used in PVsyst[99]

Parameter	Specification	Design / Engineering Basis
Table configuration	4-panel portrait (4P)	High-density AgriPV layout enabling agricultural access
Mounting orientation	Fixed tilt, south-facing (lat-adjusted)	Yield optimisation under AgriPV constraints
Tilt angle	9.1°	Optimised to balance solar yield, inter-row shading, and crop light transmission
Row pitch (centre-to-centre)	12.5 m	Defined in main report; ensures machinery access
Clear aisle width	~7.29 m	Row pitch minus table width (Estimated table width ~5.21 m Derived from module dimensions)
Ground Coverage Ratio (GCR)	30-50% (Realistic number for AgriPV may vary)	Land-use optimisation for AgriPV
Light Transmission Ratio (LTR)	~24.7%	Inherent to GCR; light available to crop zone
Front edge height	~3.5 m above ground	Satisfies agricultural machinery clearance
Rear edge height[100]	~5.0 m above ground	Enhances airflow and bifacial rear-side capture
Height differential	~1.5 m	Improves ventilation and self-shading control
Structural material	Hot-dip galvanised steel (assumed)	O&M durability; corrosion protection
Foundation type	Driven piles (assumed)	Site-specific verification required
Agricultural access clearance	~3.5 m	Compatible with standard tractors and implements

99 99 The results are indicative and may vary based on site location, latitude, climatic conditions, solar resource availability, system design, and operating conditions, cropping mechanism and crop yield.

100 May not be practical due to wind tolerance and structure strength and project cost economics. The system height is usually max 3-3.5 m

System Comparison – Arid Zone

Table D10: System Comparison for Arid Zone — Minya Governorate, Upper Egypt

Parameter	Elevated AgriPV System	Polyhouse-Integrated PV	Vertical PV System
Structural configuration	4P portrait, elevated fixed tilt	PV integrated on polyhouse roof	East–West vertical mounting
Mounting height (typ.)	~2.5–3.0 m		
Primary irradiance gain	Front + bifacial rear-side	Front-side dominant	Morning & evening capture
Soiling loss assumption	Moderate–High	Moderate	Low–Moderate
Thermal behaviour	Improved ventilation	Heat accumulation risk	Lower module temperature
Bifacial gain potential	High	Low	Minimal
Specific generation[101]	~1856 kWh/kWp/year		1092 kWh/kWp/year
Advantages of the system	• High energy potential due to strong direct irradiance • Elevated clearance enhances airflow, reducing temperature losses • Higher rear-side bifacial gain due to exposed soil and high albedo	• Provides crop protection from extreme heat and radiation • Enables controlled agriculture in harsh climates	• Lower soiling accumulation compared to tilted systems • Reduced overheating due to vertical orientation
O&M aspect in the system	• Frequent panel cleaning due to dust and sand accumulation • Inspection of structural members for thermal expansion and fatigue • Monitoring inverter derating during high-temperature periods	• Regular ventilation checks to manage heat buildup • Accelerated inspection cycles for electrical components • Higher material degradation risk due to trapped heat	• Reduced soiling frequency compared to tilted systems • Periodic alignment and anchorage stability checks • Wind-load inspections after extreme events

101 Specific generation values are reference figures derived from selected case studies and may vary across locations. Actual performance depends on local solar irradiance, climatic conditions, system configuration, and ground albedo, which is influenced by underlying soil properties, vegetation type, crop cover, and seasonal changes.

D2. Illustrative AgriPV system designing: Tropical Zone — Hyderabad, Telangana

Executive Summary

This study applies the project's crop-selection methodology to a 0.25-hectare peri-urban parcel in Southern Hyderabad (Ranga Reddy area), Telangana, on the Deccan Plateau. The aim is to shortlist the crops best suited to be grown beneath an AgriPV array here, given the site's extreme pre-monsoon heat, monsoondependent but groundwater-stressed water supply, degraded low-organic-matter soils, small holding size, and its position inside the fresh-produce and floriculture belt that feeds the Hyderabad market.

Figure 40: Tropical zone illustrative site highlighted on map



Following the framework strictly, a longlist of crops grown across Telangana and the peri-urban Hyderabad horticulture belt was compiled, screened through the non-negotiable technical prerequisites (shade tolerance and low-to-medium height), and the survivors scored against eight weighted parameters. The weightings were re-calibrated to this site's binding constraints: a **critical groundwater-depletion crisis** (water weighted highest), **extreme heat** (climate resilience high), and a **high-value peri-urban market** (demand/value high). Because soil health is a flagged concern and market access is effectively guaranteed by proximity to the city, crop-rotation value was raised and 'area under cultivation' lowered relative to the illustrative defaults.

Result. The top-scoring crops for AgriPV at this site are **leafy greens** (spinach, amaranth, coriander, fenugreek) and **marigold / floriculture**, followed closely by **chillies and turmeric**, then **tomato and brinjal**. This reflects a clear logic: under a severe water constraint and intense heat, fast-cycle, low-water, shade-loving crops that also command strong daily urban demand rise to the top, while high-value spices and flowers exploit the Hyderabad market. Paddy/wheat in this region's are most water-intensive crop and are crops the site should decide based on resource availability

Site Context and Key Constraints

The parcel is a 50 m × 50 m plot (2,500 m^2 / 0.25 ha) at 17.3303°N, 78.4110°E, on the Deccan Plateauagricultural fringe of southern Hyderabad — a small holding typical of peri-urban Telangana. Its key characteristics, from the supplied site brief, are summarized below.

Table D11: Illustrative Site Details for Tropical Zone — Hyderabad, Telangana

Parameter	Detail
Climatic zone	Tropical Savanna
Elevation	~530–550 m ASL (Deccan Plateau).
Temperature	Annual mean ~26–27 °C. Summer (Mar–May) 35–44 °C daily max (extreme heat); Monsoon (Jun–Sep) 28–34 °C; Winter (Nov–Feb) 15–20 °C min, 28–32 °C max. More than 200 days/year above 30 °C.
Precipitation	750–900 mm/yr, highly seasonal — ~80% during the SW Monsoon (Jun–Oct); dry season Nov–May (<30 mm/ month); pre-monsoon thunderstorms (Apr–May).
Irrigation	Mixed — bore wells (dominant, Deccan hard-rock aquifer, declining tables), limited canal (Nagarjuna Sagar / Srisailam command), farm ponds. Groundwater depletion is a critical crisis.
Soil type	Red Soils (Alfisols) dominant on granite-gneiss; pockets of Black Cotton Soils (Vertisols) in low-lying areas.
Soil texture & pH	Red: sandy loam to sandy clay loam, pH 6.5–7.5. Black: clay to clay loam (montmorillonite-rich), pH 7.5–8.5.
Organic matter	Low (0.3–1.0%) — intense mineralisation under high temperatures; a major soil-health concern.
Soil depth	Red soils shallow–moderate (0.3–0.8 m over weathered granite); black soils deep (1.0–3.0 m) but with severe shrink-swell.
Growing seasons	Kharif / vanakalam (monsoon, largely rainfed) + Rabi / yasangi (winter, irrigated where a bore well exists); increasing shift toward commercial horticulture.
Farming system	Smallholder-dominant (1–3 acres typical); rainfed kharif + irrigated rabi; growing commercial horticulture and poultry integration; significant tenant/lease farming.
Key risks	Extreme pre-monsoon heat (42–44 °C); erratic monsoon (drought and flood years); rapidly declining bore-well tables; soil degradation (low OM, red-soil erosion); cyclonic influence (Oct–Nov Bay of Bengal cyclones).

What the site tells us about priorities

- **Water is the binding constraint, and it is a depleting one:** the site sits on a hard-rock Deccan aquifer with rapidly falling bore-well tables, so a crop's water demand — and its ability to turn panel shade into real irrigation savings — is decisive, and flooded paddy is effectively disqualified.
- **Extreme pre-monsoon heat** (42–44 °C, 200+ days above 30 °C) is the primary agronomic hazard, and it is exactly what an overhead array mitigates, favouring crops that gain from that protection.
- **Peri-urban Hyderabad market** gives assured, highvalue outlets for fresh vegetables, leafy greens and flowers — so market value per unit area, not regional scale, drives the economics. Fourth, **soil health is explicitly degraded** (0.3–1.0% organic matter, redsoil erosion), which raises the value of nitrogen-fixing and soil-restoring rotations.

Methodology

The analysis follows the project's four-step cropselection process:

Table D12: Crop Selection Parameters and Process for Tropical Zone — Hyderabad, Telangana

Stage	What is done
1. Initial Longlist	Compile all crops currently cultivated or viable across the local climate and the peri-urban Hyderabad belt, without yet considering AgriPV constraints.
2. Technical Prerequisites Filter (Go/No-Go)	Screen every crop against two non-negotiables — high shade tolerance and low-to-medium height. Tall and sun-loving crops are removed.
3. Prioritization Matrix	Score each surviving crop from 1 (very poor fit) to 5 (excellent fit) against eight weighted parameters, using site-specific weightings. Weighted score = raw score × weightage (in percentage points)
4. Final Selection	Rank crops by total weighted score; the highest scorers form the recommended shortlist.

Step 1 — Initial Longlist

Drawing on Telangana state and PJTSAU crop profiles, district horticulture data for the Hyderabad feeder belt (Ranga Reddy, Medak, Mahbubnagar), and Telangana Horticulture Department programmes, the crops grownor established in and around the site were compiled.

Telangana's field agriculture is dominated by rice, maize, cotton, pulses, ground nut and chillies; the peri-urban belt around Hyderabad additionally supports a large and growing base of vegetables, spices and floriculture that feed the city market.

Table D13: Long List of Crops considered for Tropical Zone — Hyderabad, Telangana

Group	Crops on the longlist
Cereals / staples	Rice (paddy), maize, sorghum (jowar)
Commercial field / oilseed	Cotton, groundnut, sesame, castor, sunflower, soybean, sugarcane
Pulses	Red gram, green gram, black gram, Bengal gram
Vegetables	Tomato, brinjal, okra, chillies, cabbage, cauliflower, cucumber, carrot, radish, beans, gourds, onion
Leafy greens	Spinach, amaranth, coriander, fenugreek
Spices / rhizomes	Turmeric, ginger, coriander seed
Floriculture	Marigold, jasmine, chrysanthemum, crossandra, rose
Fruit / perennial	Mango, banana, guava, sweet orange, pomegranate, papaya
High value / other	Moringa (drumstick), lemongrass, aloe vera, mulberry (sericulture), medicinal & aromatic plants

Step 2 — Technical Prerequisites Filter (Go / No-Go)

Each longlisted crop (or crop group) is screened against the two non-negotiable prerequisites — **high shade tolerance** and **low-to-medium height**. Tall and sundemanding crops are eliminated regardless of local importance. At this site the water crisis reinforces the filter: the most water-hungry crop, paddy, also fails on shade and is the clearest crop to replace.

Table D14: Crops screening framework for Tropical Zone — Hyderabad, Telangana

Crop	Shade tolerance	Height / stature	Verdict	Rationale
Rice (paddy)	Low	Medium; needs standing water	**No-Go**	Sun-loving and extremely water-intensive; the groundwater crisis makes flooded paddy the least suitable — the prime crop to replace.
Maize / sorghum	Low	Tall (2–3 m)	**No-Go**	Sun-loving C4 cereals; height conflicts with the array.
Cotton	Low	Medium–tall	**No-Go**	Sun-demanding; yield falls sharply under heavy shade.
Sugarcane	Low	Very tall	**No-Go**	Tall and very water intensive.
Sunflower / castor	Low	Tall	**No-Go**	Tall, sun-tracking / sun-loving.
Mango, banana, citrus, etc.	n/a	Tall trees, perennial	**No-Go**	Tree height incompatible (orchard inter-row PV is a separate case).
Groundnut	Med	Low	**Go**	Low stature but sun-loving; acceptable under light shade, better in vertical inter-rows.
Turmeric / ginger	High	Low	**Go**	Shade-loving rhizomes; high-value spices; proven in Indian AgriPV.
Leafy greens (spinach, amaranth, coriander, fenugreek)	High	Low	**Go**	Champion shade crops; very short cycles; strong daily urban demand.
Chillies	Med–High	Low–medium	**Go**	Tolerate 35–50% PAR reduction; proven in winter AgriPV; high value.
Tomato	Med	Medium	**Go**	Proven under Indian AgriPV; heat relief limits flower drop; water-use-e iciency gains.
Brinjal (eggplant)	Med	Medium	**Go**	Semi-shade tolerant; proven; steady peri-urban demand.
Okra (bhendi)	Med	Medium	**Go**	Proven in Gujarat summer AgriPV; a deficit vegetable in Telangana.
Cabbage / cauliflower, carrot / radish	Med–High	Low	**Go**	Cool-season brassicas and root vegetables; shade-tolerant.
Pulses & beans (green gram, cluster beans)	Med	Low–medium	**Go**	Legumes fix nitrogen — valuable for the low-OM soil; proven in rotation.
Gourds (bottle, ridge, bitter)	Med	Vine, trellised low	**Go**	Cucurbits; fruiting needs moderate light; bottle gourd proven in Indian AgriPV.

Table D14: (continued) Crops screening framework for Tropical Zone — Hyderabad, Telangana

Crop	Shade tolerance	Height / stature	Verdict	Rationale
Marigold	Med	Low	**Go**	High-value flower with strong Hyderabad demand; also, a nematode-suppressant rotation crop.
Chrysanthemum / crossandra / jasmine	Med	Low shrub	**Go**	Floriculture; partial-shade tolerant; high value.
Lemongrass / aloe vera / MAPs	High	Low	**Go**	Aromatic/medicinal; shade-tolerant and low-water; shade can raise oil content.
Moringa (drumstick)	Med	Tall but prunable	**Go**	Performs well in Indian AgriPV trials if kept pruned to height.

Outcome of the filter. To keep the prioritization matrix decision-focused, six finalists were carried into full scoring — chosen to represent the best of the highvalue, water-sensible, shade-suited options for a periurban plot: **leafy greens, marigold, chillies, turmeric, tomato and brinjal**. Okra, gourds, cool-season vegetables, pulses, moringa and aromatic/medicinal plants remain strong secondary and rotation options discussed in Section 9.

Step 3 — Prioritization Matrix

Weighting rationale: The framework instructs users to adjust the weightage column to the project's goals. Theweightings below are re-calibrated to this site's constraints (Section 2.1). The main changes from the illustrative defaults are: **Water & Irrigation Needs raised to 25%** (a genuine groundwater-depletion crisis); Ease of Mechanization cut to 5% (a 0.25-ha holding gains little from machinery); **Crop Rotation & Intercropping raised to 10%** (soil health is a flagged concern — low OM and red-soil erosion); and Area Under Cultivation cut to 5% (peri-urban proximity to Hyderabad assures market access, so established regional scale matters less). **Level of Demand / Value stays high at 25%** to reflect the high-value urban market. Weights sum to 100%.

Table D15: Customized Weighting Rationale for Crop Selection Based on Site-Specific Constraints for Tropical Zone — Hyderabad, Telangana

Parameter	Weight	Rationale (site-specific)
Resilience to Climate Change	**20%**	Extreme pre-monsoon heat (42–44 °C, 200+ days above 30 °C) is the top hazard; panel shade protection is a core value proposition, so this stays high.
Ease of Mechanization	**5%**	A 0.25-ha smallholding worked largely by hand gains little from mechanisation.
Water & Irrigation Needs	**25%**	Raised. Bore-well tables on the hard-rock aquifer are falling fast; low water demand and shade-driven savings are the single most important technical factor.
Crop Rotation & Intercropping	**10%**	Raised. Organic matter is only 0.3–1.0% and red soils erode; nitrogen-fixing and soil-restoring rotations (and nematode-suppressant crops) have real value here.
Labour Intensity	**5%**	Labour is available and horticulture/floriculture are labour absorbing; high labour need is only a mild negative.

Table D15: (continued) Customized Weighting Rationale for Crop Selection Based on Site-Specific Constraints for Tropical Zone — Hyderabad, Telangana

Parameter	Weight	Rationale (site-specific)
Lifespan of the Crop	**5%**	Two-plus cropping windows a year favour short-cycle crops that allow rapid turnover on a small plot.
Level of Demand (Value)	**25%**	High per-unit value in the Hyderabad fresh-produce and floriculture market is the primary route to income from a small holding; kept at the top weight.
Area Under Cultivation	**5%**	Reduced. Being inside the city's feeder belt, market access is assured regardless of a crop's established regional scale, so this signals less than usual.
Total	**100%**	

Prioritization Matrix (scoring): Scores 1–5. The bottom row is the total weighted score (Σ score × weight), out of a maximum of 500 and directly comparable to the illustrative Table 5 total of 420.

Table D16: Crop prioritization scoring matrix for Tropical Zone — Hyderabad, Telangana

Parameter	Wt %	Leafy greens	Marigold	Chillies	Turmeric	Tomato	Brinjal
Resilience to Climate Change	20	5	4	4	5	5	4
Ease of Mechanization	5	3	2	2	2	3	3
Water & Irrigation Needs	25	5	4	4	3	3	3
Crop Rotation & Intercropping	10	4	5	3	3	2	2
Labour Intensity	5	3	2	2	2	2	3
Lifespan of the Crop	5	5	4	3	3	4	4
Level of Demand (Value)	25	3	5	5	5	4	4
Area Under Cultivation	5	4	3	5	4	5	5
Total Weighted Score	**100**	**415**	**410**	**395**	**385**	**365**	**350**

Step 4 — Final Selection and Ranked Shortlist

Ranking the six finalists by total weighted score gives the shortlist below. The top tier is tight: leafy greens andmarigold lead, with chillies and turmeric close behind, and tomato and brinjal forming a solid vegetable base.

Table D17: Final list of crops shortlisted for Tropical Zone — Hyderabad, Telangana

Rank	Crop	Score /500	Why
1	**Leafy greens (spinach, amaranth, coriander, fenugreek)**	**415**	Best all-round fit under a water crisis: very low water per 30–45-day cycle, multiple crops a year, champion shade tolerance, and strong daily demand in the city. Lower unit value is its only real limitation.
2	**Marigold / floriculture**	**410**	Very high value per unit area into Hyderabad's festival, temple and garland market; partial shade extends bloom; and it doubles as a nematode-suppressant that restores soil health — hence its top rotation score.
3	**Chillies**	**395**	High-value, storable (dried) crops with a large Telangana production base and proven winter AgriPV performance; moderate water need.
4	**Turmeric**	**385**	Shade-loving, high-value spice, storable and export-relevant; a longer single cycle and moderate water hold it just behind.
5	**Tomato**	**365**	Huge peri-urban demand and strong heat-relief / water-use-e iciency gains under shade; price volatility and solanaceous disease/rotation need temper it.
6	**Brinjal (eggplant)**	**350**	Steady staple demand and good semi-shade tolerance; solanaceous rotation constraints and moderate water place it sixth.

Recommended primary shortlist: leafy greens and marigold, with chillies and turmeric as high-value companions and tomato / brinjal as proven vegetable staples, plus a nitrogen-fixing pulse in rotation to rebuild organic matter. This mix maximises income per unit of scarce groundwater while turning the site's intense heat into an advantage through panel shade.

Crop Recommendations by AgriPV Configuration

The ranking in Steps 1–4 assumes an **elevated (overhead)** array. Because the physical structure dictates the light and microclimate the crop receives, the best-fit crop set changes with the configuration. The three configurations of interest are compared below and then discussed in turn, tailored to this Hyderabad site.

Table D18: Comparison of Crop Suitability Across AgriPV System Configurations for Tropical Zone — Hyderabad, Telangana

Configuration	Light / shade regime	Recommended crops (this site)	Key rationale
Elevated (overhead)	Moderate–high partial shade beneath panels (≈ 25–50% ground-coverage ratio).	**Leafy greens, marigold, chillies, turmeric, tomato, brinjal.**	Matches the Step 3 matrix ranking. Shade-tolerant, high-value crops convert heat protection and reduced evaporation into real water savings on the small plot. Form used in the PJTSAU Hyderabad AgriPV pilot.
Vertical (bifacial, E/W-facing)	Near-full sun in wide inter-row strips; brief morning & evening shade bands.	**Groundnut, pulses (red gram, green gram), millets/sorghum fodder, plus the rainfed kharif field crops.**	Sunlit strips let the traditional rainfed monsoon field crops continue, so the farmer keeps staple/pulse production while adding energy with almost no land loss — and legumes rebuild organic matter soil. Panels stay clean and machine access is easy.

Table D18: (continued) Comparison of Crop Suitability Across AgriPV System Configurations for Tropical Zone — Hyderabad, Telangana

Configuration	Light / shade regime	Recommended crops (this site)	Key rationale
Polyhouse (semi-transparent roof PV, ~25% cover ratio)	Controlled climate; ~25– 40% PAR reduction with stabilised midday temperature.	**Capsicum (coloured bell pepper), salad tomato, cucumber, exotic leafy greens, strawberry, and cut flowers (gerbera, rose, carnation, chrysanthemum).**	Premium, o -season, export-grade horticulture and floriculture for the city. Roof PV curbs the 42–44 °C midday heat; drip/hydroponics give the tightest water control — critical under the groundwater crisis. Highest value and water-use e iciency, but highest capital cost.

Elevated (overhead) AgriPV — primary recommendation

- Panels are mounted 4–5 m above ground so people (and any small machinery) can work underneath, with crops grown directly beneath in partial shade. This is the configuration the Step 3 matrix was built around, so its recommendation is the Step 4 shortlist: **leafy greens and marigold as primary crops, chillies and turmeric as high-value companions, and tomato and brinjal as vegetable staples**. These crops tolerate or benefit from 30–50% light reduction, and at this hot, waterscarce site the shade delivers its greatest value — lower canopy temperature, reduced flower drop and evaporation, and protection from pre-monsoon heat. Fruiting crops (tomato, chilli, brinjal) belong in lowerdensity rows (≈ 25–50% ground-coverage ratio) so fruit set is not light-limited. This is the recommended default for a small, high-value peri-urban plot, and is precisely the form of the 10.8 kWp elevated AgriPV pilot running at PJTSAU in Hyderabad under semiarid, water-stressed conditions.

Vertical (bifacial) AgriPV

- Bifacial panels are mounted vertically in east/ westfacing rows, occupying only about 500mm (0.5 m)[102] to avoid, flooding damage, weed interference, with wide (roughly 8–12 m) crop strips between rows that receive close to full sunlight for most of the day. This flips the crop logic: crops that **failed the overhead shade filter because they are sun-loving now become suitable again**. For this site that re-opens the region's rainfed field crops — **groundnut, pulses (red gram, green gram), and millets/sorghum for fodder** — letting the farmer continue the traditional monsoon (kharif) cropping while generating power. It is the natural choice where the goal is to keep growing staples and pulses rather than to maximise per-drop water savings, and the legumes it favours directly help rebuild the site's depleted soil organic matter. India already has vertical AgriPV demonstrations (for example, the NISE pilot near Gurgaon), and east/west verticals stay clean and leave the field fully workable. The trade-o is that the crop receives less of the heat- and water-saving shade benefit than under an overhead array. ¸

102 IEA-PVPS Task 13 Report, Bifacial Photovoltaic Modules and Systems: Experience and Results from International Research and Pilot Applications 2021

Polyhouse / greenhouse-integrated AgriPV

- Here semi-transparent PV modules are built into the roof of a protected greenhouse (polyhouse), typically at ~25% cover ratio, so the crop grows in a controlled environment beneath partial roof shading. In hot, high-light climates like Hyderabad's this keeps yields of even light-demanding crops within a small penalty while the roof PV **stabilises midday temperature and prevents heat-induced photoinhibition** — a real gain against 42–44 °C summers — and the enclosed system gives the **highest water-use e iciency of the three configurations** through drip or hydroponic irrigation, which matters most under the groundwater crisis.
- The best-fit crops are **premium protected horticulture and floriculture for the city**: capsicum (coloured bell peppers), salad/cherry tomato, cucumber, exotic and baby leafy greens, strawberries, and high-value cut flowers such as gerbera, rose, carnation and chrysanthemum. This directly matches the site brief's noted shift toward commercial horticulture, and Telangana already subsidises polyhouse and shade-net structures. It delivers the highest value per square metre and the tightest water control but carries the **highest capital cost and a cooling requirement**, so it suits growers with access to horticulture-mission support, cooperatives, or contract-export arrangements rather than the most capital-constrained smallholders.

Matching configuration to the grower at this site: On 0.25-ha peri-urban plot the three can be complementary: an **elevated** block for the high-value leafy-green / marigold / spice core; a few **vertical** rows to keep rainfed pulses and groundnut going and rebuild soil through legume rotation; and a compact polyhouse unit for premium floriculture and protected vegetables. Given the small holding, the severe water constraint and the strong city market, the highest-return combination for most growers here is an **elevated high-valuehorticulture block paired with a compact polyhouse for floriculture** — with vertical rows added only if the farmer wishes to retain traditional field cropping. The choice ultimately follows the owner's capital and objective: maximum value per drop of water (elevated), continuity of rainfed staple/pulse production (vertical), or premium protected export crops (polyhouse).

Crop-Specific Rationale and Implementation Notes

- **Leafy greens (top pick):** Spinach, amaranth, coriander and fenugreek complete a cycle in 30–45 days, allowing several harvests a year with very low water per cycle — the ideal profile under a depleting aquifer. They are among the most shade-tolerant of all crops (shade reduces bolting and heat stress), and Hyderabad's daily demand for fresh greens, reinforced by Telangana's urban-vegetable programmes, gives an assured outlet. The main watch-point is perishability, which the site's closeness to the city market largely neutralises.
- **Marigold and floriculture (top pick):** Marigold o ers very high value per unit area into Hyderabad's year-round festival, temple and garland trade, tolerates partial shade (which can extend flowering), and — unusually — improves the soil, as marigold is a well-known nematode-suppressant and useful rotation crop, which is why it scores highest on rotation value at this degraded-soil site. Jasmine, chrysanthemum and crossandra are further highvalue floriculture options. The main watch-points are perishability and timing supply to festival peaks.
- **High-value companions and rotation crops:** Turmeric and ginger are shade-loving, high-value, storable rhizomes well suited to the shaded understorey; chillies are a high-value, storable Telangana staple proven in winter AgriPV; and tomato, brinjal and okra are dependable peri-urban vegetable earners. A nitrogen-fixing pulse (green gram or red gram) should be worked into the rotation to rebuild the site's low organic matter, and aromatic/medicinal crops (lemongrass, aloe vera) are low-water niche options.
- **The crop to move away from:** Paddy is the least suitable crop for this site and the clearest one to replace. It is both sun-loving (failing the shade filter) and by far the most water-intensive option, drawing directly on the collapsing bore-well aquifer. An AgriPV-enabled shift from paddy to the shaded, lowwater, high-value crops above is the single largest sustainability and income gain available here.

System design pointers for this site

- Use **drip / micro-irrigation** to bank the ~30% reduction in soil evaporation that shade provides — the core water argument for AgriPV in this waterstressed setting.
- Target a **moderate ground-coverage ratio (≈ 25– 50%)** so leafy greens, flowers and spices get watersaving shade while fruiting vegetables keep enough light.
- Design for the monsoon and cyclone season: **use the array and gutters** to harvest heavy Jun–Oct rain into a farm pond for dry-season use and specify structures for Oct–Nov cyclonic wind loads.
- Exploit the very high solar resource and schemes such as **PM-KUSUM and Telangana's 'solar as a third crop' initiative** to strengthen dual-use economics.
- **Rebuild soil organic matter with legume rotations, mulching and marigold**, given the flagged 0.3–1.0% baseline and red-soil erosion.

Limitations. This is a desk study using an illustrative parcel; scores are expert judgements on a 1–5 scale andare approximate. Real deployment should confirm the bore-well yield and any local water-use regulation, run a one-to-two-season on-site trial (crop response to shade is site- and cultivar-specific and varies year to year), secure market and buyer channels (especially for perishable greens and flowers), and finalise array geometry — including monsoon drainage and cyclonic wind design — with a coupled energy-yield and agronomy model. Weightings should be revisited with the grower if priorities (for example, maximising employment or retaining staple self-su iciency) di er from those inferred here.

Solar PV System Design Basis and Structural Assumptions

All PV energy yield simulations presented in this study are based on a uniform AgriPV structural and electrical configuration, applied consistently across all evaluated climatic zones (arid, semi-arid, tropical, continental, and temperate). This approach ensures that observed performance variations are attributable primarily to climate and irradiation characteristics, rather than design inconsistencies.

Table D19: Standard Structural Parameters Used in PVsyst[103]

Parameter	Specification	Design / Engineering Basis
Table configuration	4-panel portrait (4P)	High-density AgriPV layout enabling agricultural access
Mounting orientation	Fixed tilt, south-facing (lat-adjusted)	Yield optimisation under AgriPV constraints
Tilt angle	9.1°	Optimised to balance solar yield, inter-row shading, and crop light transmission
Row pitch (centre-to-centre)	12.5 m	Defined in main report; ensures machinery access
Clear aisle width	~7.29 m	Row pitch minus table width (Estimated table width ~5.21 m Derived from module dimensions)
Ground Coverage Ratio (GCR)	30-50% (Realistic number for AgriPV may vary)	Land-use optimisation for AgriPV
Light Transmission Ratio (LTR)	~24.7%	Inherent to GCR; light available to crop zone

103 The results are indicative and may vary based on site location, latitude, climatic conditions, solar resource availability, system design, and operating conditions, cropping mechanism and crop yield.

Table D19: (continued) Standard Structural Parameters Used in PVsyst

Parameter	Specification	Design / Engineering Basis
Front edge height	~3 m above ground	Satisfies agricultural machinery clearance
Rear edge height[104]	~3.5 m above ground	Enhances airflow and bifacial rear-side capture
Height differential	~1.5 m	Improves ventilation and self-shading control
Structural material	Hot-dip galvanised steel (assumed)	O&M durability; corrosion protection
Foundation type	Driven piles (assumed)	Site-specific verification required
Agricultural access clearance	≥ 3.5 m	Compatible with standard tractors and implements

System Comparison – Tropical Zone

Table D20: System Comparison for Tropical Zone — Hyderabad, Telangana

Parameter	Elevated AgriPV System	Polyhouse-Integrated PV	Vertical PV System
Environmental characteristic	High humidity & rainfall	Controlled microclimate	High di use irradiance
Soiling loss assumption	Low–Moderate	Low	Very low
Thermal stress	Moderate	Moderate–High	Low
Rear-side gain potential	Medium	Very low	Negligible
Structural suitability	High (flood-safe clearance)	High for horticulture	Moderate
O&M complexity	Moderate	High	Low
Specific generation (kWh/kWp)[105]	~ 1644 kWh/kWp/year		870 kWh/kWp/year

104 May not be practical due to wind tolerance and structure strength and project cost economics. The system height is usually max 3-3.5 m

105 Specific generation values are reference figures derived from selected case studies and may vary across locations. Actual performance depends on local solar irradiance, climatic conditions, system configuration, and ground albedo, which is influenced by underlying soil properties, vegetation type, crop cover, and seasonal changes

Table D20: (continued) System Comparison for Tropical Zone — Hyderabad, Telangana

Parameter	Elevated AgriPV System	Polyhouse-Integrated PV	Vertical PV System
Advantages of the system	• Elevated structure improves airflow and humidity management • Reduced flood risk • Lower soiling due to rainfall washing	• Strong synergy with tropical horticulture • Protection from excessive rainfall	• Very low soiling due to frequent rain • Minimal obstruction to cropping
O&M aspect in the system	• Corrosion monitoring of structural steel and connectors • Vegetation control beneath elevated structures • Post-monsoon electrical and earthing inspections	• Frequent inspection of cables and junction boxes due to humidity • Condensation and drainage management • Enhanced corrosion protection measures	• Low soiling due to natural rainfall cleaning • Corrosion checks at mounting bases • Periodic electrical insulation testing

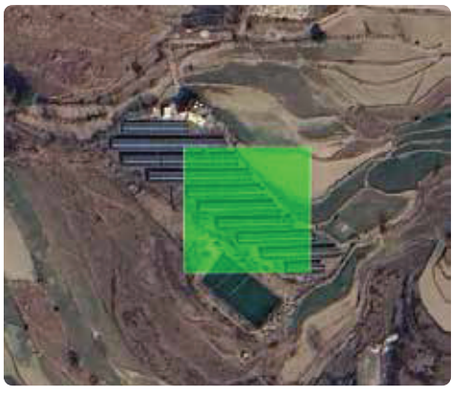


D3. Illustrative AgriPV system designing: Temperate Zone — Jahu, Hamirpur District, Himachal Pradesh

Executive Summary

This study applies the project's crop-selection methodology to a **0.25-hectare terraced parcel in Jahu village, Hamirpur District, in the lower Shivalik / sub-montane mid-hills of Himachal Pradesh**. The aim is to shortlist the crops best suited to be grown beneath an AgriPV array here, given the site's cool temperate climate, abundant but highly seasonal monsoon rainfall, hail- and frost-prone weather, small, terraced holdings, and — above all — its comparative advantage in high-value o -season vegetables, spices and flowers for the plains markets.

Figure 41: Temperate zone illustrative site highlighted on map



Following the framework strictly, a longlist of crops grown across Himachal's mid-hills and the Hamirpur belt was compiled, screened through the nonnegotiable technical prerequisites (shade tolerance and low-to-medium height), and the survivors scored against eight weighted parameters. The weightings were recalibrated to this site's realities, which di er sharply from an arid site: because rainfall is abundant (1,100– 1,500 mm/yr), **water is no longer the binding constraint** and its weight is lowered; instead **climate resilience** (frost, hailstorms and monsoon erosion — hazards that panels physically shield against) and **market value** (the o -season premium) become the two dominant criteria, with the crop's fit to Himachal's established horticulture supply chains also weighted more heavily for these distant-market crops.

Result. The top-scoring crops for AgriPV at this site are **ginger** and **floriculture**, followed by **o -season legumes** (garden pea, French bean), then capsicum and tomato, with **leafy greens** as fast intercrops. The logic is distinct from a temperate hill site: with water abundant, selection is driven by which high-value crops best exploit the cool-season / o -season premium and gain most from the array's hail, frost and rain protection. The crops to move **away** from are rainfed subsistence maize and wheat — low-value, sun-loving, and precisely the shift Himachal's horticulture policy already encourages.

Site Context and Key Constraints

The parcel is a 50 m × 50 m plot (2,500 m^2 / 0.25 ha) at 31.5787°N, 76.7366°E, in the lower Shivalik / submontane mid-hills — a small, terraced holding typical ofHimachal Pradesh. Its key characteristics, from the supplied site brief, are summarized below.

Table D21: Illustrative Site Details for Temperate Zone — Jahu, Himachal Pradesh

Parameter	Detail
Climatic zone	Temperate.
Elevation	~550–700 m ASL (lower mid-hills, not high-altitude Himalaya).
Temperature	Annual mean ~20–22 °C. Summer (May–Jun) 35–42 °C daily max (hot, dry pre-monsoon); Winter (Dec–Feb) 4– 10 °C daily min with occasional frost in valley bottoms; Monsoon (Jul–Sep) 25–32 °C with high humidity.
Precipitation	1,100–1,500 mm/yr, highly seasonal — ~80% during the SW Monsoon (Jul–Sep); dry winter (Nov–Feb, <50 mm/ month); pre-monsoon thunderstorms (Apr–Jun).
Irrigation	Limited — primarily rainfed (kharif) plus small tube wells and gravity-fed channels (kuhls) for supplemental rabi irrigation; water scarcity concentrated in the pre-monsoon (Apr–Jun).
Soil type	Likely Inceptisols / Brown Hill Soils, developed from Shivalik sandstone/clay weathering; possibly some colluvial deposits.
Soil texture	Sandy loam to clay loam; variable with slope position; stony in places.
Soil depth	Variable — 0.3–1.0 m on slopes; deeper (1.0–2.0 m) on terraced valley floors.
Growing seasons	Kharif (monsoon, largely rainfed) + rabi (winter, supplemental irrigation); strong and growing o -season vegetable and fruit window for plains markets.
Farming system	Smallholder, mixed subsistence + emerging commercial horticulture; terraced fields; limited mechanisation (power tillers, small tractors); shift toward o -season vegetables and fruit for plains markets, supported by state policy.
Key risks	Pre-monsoon drought stress (Apr–Jun); intense monsoon rainfall (erosion, waterlogging); occasional winter frost; hailstorms (Mar–Apr); small/fragmented landholdings; terrain limitations for mechanisation.

What the site tells us about priorities

- **Water is not the binding constraint here:** at 1,100–1,500 mm/yr the site is largely rainfed, and scarcity is only seasonal (pre-monsoon).
- **Climate hazards are the primary threat:** frost, spring hailstorms, pre-monsoon drought and erosive monsoon downpours all damage crops, and an overhead array physically shields against hail, frost radiation and rain-splash — making resilience a top criterion.
- **Comparative advantage is the o -season premium:** the cool hill climate lets growers supply vegetables, flowers and spices when the plains cannot, commanding high prices — so market value is co-dominant.
- Because these crops travel to **distant plains markets** rather than a city next door, fit with Himachal's established horticulture supply chains (grading, cold-chain, mandi linkage) matters more than at a peri-urban site.

Methodology

The analysis follows the project's four-step cropselection process:

Table D22: Crop Selection Parameters and Process for Temperate Zone — Jahu, Himachal Pradesh

Stage	What is done
1. Initial Longlist	Compile all crops currently cultivated or viable across the local climate and the Himachal mid-hills, without yet considering AgriPV constraints.
2.Technical Prerequisites Filter (Go/No-Go)	Screen every crop against two non-negotiables — high shade tolerance and low-to-medium height. Tall and sun-loving crops are removed.
3. Prioritization Matrix	Score each surviving crop from 1 (very poor fit) to 5 (excellent fit) against eight weighted parameters, using site-specific weightings. Weighted score = raw score × weightage (in percentage points), exactly as in Table 5.
4. Final Selection	Rank crops by total weighted score; the highest scorers form the recommended shortlist.

Step 1 — Initial Longlist

Drawing on Himachal Pradesh crop profiles and the district horticulture base for Hamirpur, the crops grown or established in and around the site were compiled. Hamirpur's field agriculture is dominated by rainfedmaize and wheat; the mid-hills additionally support a large and growing base of o -season vegetables, spices (notably ginger), sub-tropical / stone fruit, floriculture and medicinal plants that supply the plains markets.

Table D23: Long List of Crops considered for Temperate Zone — Jahu, Himachal Pradesh

Group	Crops on the longlist
Cereals / staples	Maize, wheat, barley, paddy (valley floors), millets
Pulses	Garden pea, French bean (rajmash), black gram (urad), horse gram (kulthi), moong, chickpea
Oilseeds	Mustard / rapeseed, toria, sesame
O -season vegetables	Tomato, capsicum (bell pepper), cauliflower, cabbage, broccoli, cucumber, okra, brinjal, radish, carrot, garlic, onion, potato (seed potato)
Leafy greens	Spinach, coriander, fenugreek, lettuce
Spices / rhizomes	Ginger, turmeric, garlic
Floriculture	Carnation, rose, gerbera, lilium, gladiolus, marigold, chrysanthemum
Fruit / perennial	Stone fruit (peach, plum, apricot, pear), citrus (orange, lemon, kinnow), mango, litchi, guava, kiwi, pomegranate
High value / other	Mushroom, strawberry, medicinal & aromatic plants (tulsi, ashwagandha, lemongrass, stevia)

Step 2 — Technical Prerequisites Filter (Go / No-Go)

Each longlisted crop (or crop group) is screened against the two non-negotiable prerequisites — **high shade tolerance** and **low-to-medium height**. Tall and sundemanding crops are eliminated regardless of local importance. Fruit trees fail the height test as underpanel crops but remain candidates for inter-row planting under a vertical or elevated array (Section 8).

Table D24: Crops screening framework for Temperate Zone — Jahu, Himachal Pradesh

Crop	Shade tolerance	Height / stature	Verdict	Rationale
Maize	Low	Tall (2–3 m)	**No-Go**	Sun-loving C4 cereal and the main subsistence crop; height conflicts with the array — a prime crop to shift away from.
Wheat / barley	Low	Medium	**No-Go**	Full-sun cereals; low value; better suited to open field or vertical inter-rows.
Paddy (valley)	Low	Medium; standing water	**No-Go**	Sun-loving and water-intensive.
Mustard / rapeseed	Low	Medium–tall	**No-Go**	Sun-demanding oilseed.
Fruit trees (stone fruit, citrus, mango)	n/a	Tall trees, perennial	**No-Go**	Tree height is incompatible as an under-panel crop (orchard inter-row PV is a separate case).
Ginger	High	Low	**Go**	Shade-loving rhizome; a leading Hamirpur mid-hill cash crop; high value; stores and ships well.
Turmeric	High	Low	**Go**	Shade-loving rhizome; high value; complements ginger.
Leafy greens (spinach, coriander, fenugreek, lettuce)	High	Low	**Go**	Champion shade crops; very short cycles; steady demand.
Garden pea / French bean	Med	Low–medium	**Go**	Cool-season legumes; high o -season value; fix nitrogen and check slope erosion.
Capsicum (bell pepper)	Med	Medium	**Go**	High-value o -season vegetable; a mainstay of Himachal protected cultivation.
Tomato	Med	Medium	**Go**	Proven under Indian AgriPV; strong o -season premium; benefits from hail / rain / sunscald protection.
Cauliflower / cabbage / broccoli	Med–High	Low	**Go**	Cool-season brassicas; shade-tolerant; established o -season crops.
Radish / carrot / turnip	Med	Low	**Go**	Root vegetables; shade-tolerant; quick.
Garlic / onion	Med	Low	**Go**	Low alliums; storable; good value.
Floriculture (carnation, rose, gerbera, lily, marigold, gladiolus)	Med	Low–medium	**Go**	High-value cut flowers; Himachal leads Indian carnation output; hail/rain protection greatly improves bloom quality.

Table D24: (continued) Crops screening framework for Temperate Zone — Jahu, Himachal Pradesh

Crop	Shade tolerance	Height / stature	Verdict	Rationale
Strawberry	Med	Low	**Go**	High-value short-season crop; grows well in Himachal with protection.
Medicinal & aromatic plants (tulsi, lemongrass, ashwagandha)	High	Low	**Go**	Shade-tolerant, low-water, high value; supported under the AYUSH mission in the Shivalik zone.
Mushroom	n/a (indoor)	Low	**Go (sep.)**	High-value Himachal crop but grown in sheds — pairs with the structure rather than under panels.

Outcome of the filter. To keep the prioritization matrix decision-focused, six finalists were carried into full scoring — chosen to represent the best of the highvalue, o -season, shade-suited options for a temperate mid-hill plot: **ginger, floriculture, o -season legumes (garden pea / French bean), capsicum, tomato and leafy greens**. Turmeric, brassicas, root vegetables, alliums, strawberries, medicinal plants and mushroom remain strong secondary and rotation options.

Step 3 — Prioritization Matrix

Weighting rationale: The framework instructs users to adjust the weightage column to the project's goals. Theweightings below are re-calibrated to this site's constraints. The main changes from the illustrative defaults are: **Water & Irrigation Needs cut to 10%** (rainfall is abundant and only seasonally scarce, so water demand discriminates little here); **Resilience to Climate Change raised to 25%** (frost, spring hail and monsoon erosion are the dominant hazards, and the array physically protects against them); **Area Under Cultivation raised to 15%** (these crops travel to distant plains markets, so fit with Himachal's established horticulture supply chains matters); and **Ease of Mechanization cut to 5%** (small, terraced, fragmented plots). **Level of Demand / Value stays high at 25%** for the o -season premium. Weights sum to 100%.

Table D25: Customized Weighting Rationale for Crop Selection Based on Site-Specific Constraints for Temperate Zone — Jahu, Himachal Pradesh

Parameter	Weight	Rationale (site-specific)
Resilience to Climate Change	**25%**	Frost, spring hailstorms (Mar–Apr), pre-monsoon drought and erosive monsoon rain are the site's defining hazards; an overhead array shields crops from hail, frost and rain-splash, so this becomes a top criterion.
Ease of Mechanization	**5%**	Small, fragmented, terraced plots with terrain limits gain little from machinery.
Water & Irrigation Needs	**10%**	Lowered. At 1,100–1,500 mm/yr the site is largely rainfed and water is scarce only in the pre-monsoon, so water demand signals far less here than at an arid site.
Crop Rotation & Intercropping	**10%**	Raised slightly. Slopes erode under intense monsoon, and soils are shallow in places; nitrogen-fixing and cover-forming rotations protect and rebuild the soil.
Labour Intensity	**5%**	Family / manual labour is available and horticulture is labour absorbing; high labour need is only a mild negative.

Table D25: (continued) Customized Weighting Rationale for Crop Selection Based on Site-Specific Constraints for Temperate Zone — Jahu, Himachal Pradesh

Parameter	Weight	Rationale (site-specific)
Lifespan of the Crop	**5%**	Short-cycle crops that fit the o -season window and allow rapid turnover on a small plot are mildly favoured.
Level of Demand (Value)	**25%**	The cool climate's o -season premium in the plains markets is the core income opportunity; kept at the top weight.
Area Under Cultivation	**15%**	Raised. Because produce ships to distant plains markets, a crop fit with Himachal's established horticulture area, grading and cold chain / mandi linkages materially aid success.
Total	**100%**	

Scoring (1 = very poor fit … 5 = excellent fit): Each finalist is scored against every parameter on the 1–5 scale, based on the research

Step 3 — Prioritization Matrix (scoring): Scores 1–5.

The bottom row is the total weighted score (Σ score × weight), out of a maximum of 500 and directly comparable to the illustrative Table 5 total of 420.

Table D26: Crop prioritization scoring matrix for Temperate Zone — Jahu, Himachal Pradesh

Parameter	Wt %	Ginger	Floriculture	O -season legumes	Capsicum	Tomato	Leafy greens
Resilience to Climate Change	25	5	5	4	5	5	4
Ease of Mechanization	5	2	2	3	2	3	3
Water & Irrigation Needs	10	3	4	4	3	3	5
Crop Rotation & Intercropping	10	3	4	5	2	2	4
Labour Intensity	5	2	2	3	2	2	3
Lifespan of the Crop	5	2	4	4	3	4	5
Level of Demand (Value)	25	5	5	4	5	4	3
Area Under Cultivation	15	5	3	4	4	5	3
Total Weighted Score	**100**	**415**	**415**	**400**	**395**	**395**	**365**

Step 4 — Final Selection and Ranked Shortlist

Ranking the six finalists by total weighted score gives the shortlist below. The top of the table is very tight: gingerand floriculture tie for first, o -season legumes follow, and capsicum and tomato tie just behind.

Table D27: Final list of crops shortlisted for Temperate Zone — Jahu, Himachal Pradesh

Rank	Crop	Score /500	Why
1	**Ginger**	**415**	A leading Hamirpur mid-hill cash crop: a shade-loving rhizome ideally suited to the panel understorey, high-value and storable, with an established supply chain to Punjab, Haryana and Delhi. A long single cycle is its only real limitation.
1	**Floriculture (carnations, rose, gerbera, lily, marigold)**	**415**	Very high value per unit area, with Himachal leading Indian carnation output; hail and rain protection from the array (or polyhouse) sharply improves bloom quality and price, and marigold adds nematode-suppressing rotation value.
3	**O -season legumes (garden pea, French bean)**	**400**	Strong o -season premium in the plains, short cycles, and — uniquely — nitrogen fixation and cover that rebuild and hold the site's sloping soils, giving the top rotation score.
4	**Capsicum (bell pepper)**	**395**	High-value o -season vegetable and a mainstay of Himachal protected cultivation; benefits strongly from hail and sunscald protection.
4	**Tomato**	**395**	Large o -season demand and an established Himachal growing base; hail, rain and sunscald protection cut cracking and disease. Price volatility and solanaceous rotation need temper it.
6	**Leafy greens (spinach, coriander, lettuce)**	**365**	The strongest technical fit — very shade-tolerant, fast and low-water — but lower unit value and perishability for distant markets cap its score; best as a fast intercrop.

Recommended primary shortlist: ginger and floriculture, with o -season legumes (garden pea / French bean) and capsicum / tomato as the high-value o -season vegetable core, plus leafy greens as fast intercrops and a legume in rotation to hold and rebuild the sloping soils. This mix turns the site's cool climate and hail/frost exposure into an advantage — the array supplies exactly the physical protection these premium crops reward — while targeting the o -season plainsmarket premium.

Crop Recommendations by AgriPV Configuration

The ranking in Steps 1–4 assumes an elevated (overhead) array. Because the physical structure dictates the light and microclimate the crop receives, the best-fit crop set changes with the configuration. The three configurations of interest are compared below and then discussed in turn, tailored to this Himachal mid-hill site.

Table D28: Comparison of Crop Suitability Across AgriPV System Configurations for Temperate Zone — Jahu, Himachal Pradesh

Configuration	Light / shade regime	Recommended crops (this site)	Key rationale
Elevated (overhead)	Moderate partial shade beneath panels (≈25–40% ground-coverage ratio; kept lower than at a desert site).	**Ginger, floriculture, o -season legumes, capsicum, tomato, leafy greens.**	Matches the Step 3 matrix ranking. In a temperate climate the headline benefit is physical protection — hail, frost radiation, rain-splash and pre-monsoon sunscald — plus season extension, rather than water saving. Keep the array relatively open so light-demanding crops still yield through the cloudy monsoon.
Vertical (bifacial, E/W-facing)	Near-full sun in wide inter-row strips; brief morning & evening shade bands.	**Maize, wheat and other cereals/fodder, mustard, and fruit-tree inter-rows.**	Sunlit strips let the sun-loving cereals and orchard rows continue, so the farmer keeps subsistence / fodder production while adding energy. Aligned along the contours, the rows also act as erosion and runo barriers on the monsoon-prone slopes — a real bonus here. Trade-o : little hail/frost protection for the crop.
Polyhouse (semi-transparent roof PV, ~25% cover ratio)	Controlled climate; partial roof shading with frost exclusion in winter and hail/ rain exclusion year-round.	**Capsicum, hybrid tomato, cucumber, exotic salad greens, strawberry, and premium cut flowers (carnation, rose, gerbera, lilium).**	The strongest fit for Himachal, whose protected-cultivation ecosystem is already heavily subsidised. The structure excludes hail and rain, holds winter warmth against frost, and extends the o -season window; semi-transparent roof PV adds energy and can run fans, drip or heating. Highest value, but highest capital cost — well matched to the state's polyhouse subsidy schemes.

Elevated (overhead) AgriPV — primary recommendation

- Panels are mounted 4–5 m above ground so people (and any power tiller) can work underneath, with crops grown directly beneath in partial shade. This is the configuration the Step 3 matrix was built around, so its recommendation is the Step 4 shortlist: **ginger and floriculture as primary crops, o -season legumes and capsicum / tomato as the vegetable core, and leafy greens as fast intercrops**. Unlike at a desert site, the array's main gift in a temperate hill climate is **physical crop protection** — it shields against spring hail, frost radiation on clear winter nights, erosive monsoon rain-splash and premonsoon sunscald — together with a longer growing window. Because the monsoon already dims the sky and temperatures are moderate, the groundcoverage ratio should be kept relatively low (≈ 25– 40%) so that light-demanding crops are not starved of radiation. This is the recommended default for the high-value core of a small, terraced plot.

Vertical (bifacial) AgriPV

- Bifacial panels are mounted vertically in east/ westfacing rows, occupying only about 500mm (0.5 m) [106] to avoid, flooding damage, weed interference, with wide (roughly 8–12 m) crop strips between rows that receive close to full sunlight for most of the day. This flips the crop logic: crops that **failed the overhead shade filter because they are sun-loving now become suitable again**. For this site that keeps the traditional **rainfed cereals (maize, wheat), fodder and mustard** in production, and leaves room for fruit-tree inter-rows, so the farmer can continue subsistence and orchard cropping while generating power. A distinctive advantage at Jahu is that, **aligned along the terrace contours, the vertical rows act as erosion and runo barriers** during the intense monsoon and as windbreaks — turning the array into a soil-conservation asset on the slopes. The trade-o is that the crop receives little of the hail and frost protection that the high-value horticulture crops most value, so vertical is best where the objective is to retain field crops rather than to grow premium protected crops.

Polyhouse / greenhouse-integrated AgriPV

- Here semi-transparent PV modules are built into the roof of a protected greenhouse (polyhouse), typically at ~25% cover ratio, so the crop grows in a controlled environment beneath partial roof shading. This is arguably the **best-matched configuration for Himachal**, whose horticulture strategy already rests on subsidised protected cultivation (state polyhouse schemes such as the Dr Y.S. Parmar Kisan Swarozgar Yojana have o ered very high subsidy support). The enclosed structure **excludes hail and rain, retains warmth against winter frost, and stretches the o -season window at both ends** — directly countering the site's defining hazards — while the semi-transparent roof PV adds electricity and can power fans, drip irrigation or gentle heating.
- The best-fit crops are p**remium protected vegetables and cut flowers**: capsicum, hybrid / cherry tomato, cucumber, exotic salad greens and strawberry, plus high-value cut flowers such as carnation (in which Himachal leads India), rose, gerbera and lilium. This matches the site brief's noted shift toward commercial horticulture and the state's existing protected-cultivation base. It delivers the highest value per square metre and the most complete weather control but carries the **highest capital cost**; the deep state subsidy for polyhouses is what makes it broadly accessible to smallholders here.

Crop-Specific Rationale and Implementation Notes

- **Ginger (co-top pick):** Ginger is a leading cash crop of Himachal's mid and low hills and is specifically established in Hamirpur, with fresh produce moving to Punjab, Haryana, Delhi and Uttar Pradesh. As a shade-loving rhizome it is ideally suited to the panel understorey, it stores and transports well, and it commands high value. The main watch-points are ensuring good drainage to avoid rhizome rot in the intense monsoon, managing soil-borne disease through rotation, and the relatively high cost of seed rhizome.
- **Floriculture (co-top pick):** Cut flowers — carnation (in which Himachal leads India), rose, gerbera, lilium, plus marigold and gladiolus — o er very high value per unit area and strong domestic and export demand. Hail and rain protection from the array or a polyhouse dramatically improves bloom quality and hence price, which is why floriculture scores so highly on resilience and value, and marigold additionally provides nematode-suppressing rotation benefit. The main watch-points are perishability and the need for reliable cold-chain and market linkage, and the fact that the premium cut flowers realise their full value under a protected structure.

106 IEA-PVPS Task 13 Report, Bifacial Photovoltaic Modules and Systems: Experience and Results from International Research and Pilot Applications 2021

- **O -season vegetables and rotation crops:** Garden pea, French bean, capsicum, tomato and the cool-season brassicas (cauliflower, cabbage, broccoli) are Himachal's flagship o -season earners, commanding a premium in the plains when those markets are out of season. Legumes are doubly valuable here, fixing nitrogen and forming a protective cover that checks erosion on the slopes, and should anchor the rotation. Leafy greens (spinach, coriander, lettuce) serve as fast, shade-tolerant intercrops, while turmeric, garlic, strawberry and medicinal / aromatic plants (tulsi, lemongrass) are further high-value options.
- **The crops to move away from:** Rainfed subsistence maize and wheat are the least rewarding crops to keep under an array: they are sun-loving (failing the shade filter), low in value, and gain little from panel protection. Himachal's horticulture policy is already steering growers from these cereals toward commercial o -season vegetables, fruit and flowers, and an AgriPV installation accelerates exactly that transition — while any cereal a household wishes to retain can be grown in the sunlit strips of a vertical array

System design pointers for this site

- **Prioritise physical protection in the layout:** position and angle panels to maximise hail, frost and rain-splash shielding over the high-value crops — the headline benefit in this climate — rather than to maximise shade.
- Keep the **ground-coverage ratio moderate (≈ 25– 40%)**: the cool climate and cloudy monsoon mean light, not heat, can become limiting, so avoid overshading light-demanding vegetables and flowers.
- Engineer for the monsoon and slope: **integrate the array with the existing terracing, align any vertical rows along the contours for erosion control**, and provide drainage and runo capture to handle intense Jul–Sep rainfall and avoid waterlogging.
- **Design for frost and hail:** allow cold-air drainage in valley bottoms and consider anti-hail netting or a polyhouse for the most sensitive high-value crops.
- Leverage state support: **Himachal's polyhouse and protected-cultivation subsidies (e.g. the Dr Y.S. Parmar Kisan Swarozgar Yojana) and MIDH horticulture schemes** materially improve the economics of the polyhouse and drip options.
- Rebuild and hold the soil: **anchor rotations with nitrogen-fixing legumes** and use mulching and cover on erosion-prone slopes.

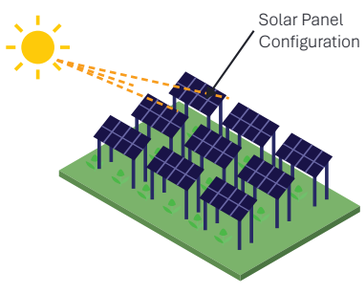
Limitations. This is a desk study using an illustrative parcel; scores are expert judgements on a 1–5 scale and are approximate. A temperate, monsoon-influenced climate carries a specific caveat: because light — not heat or water — can be the limiting factor for part of the year, over-shading can reduce yields of light-demanding crops more than at a sunny arid site, so a moderate ground-coverage ratio and a one-to-two-season on-site trial are essential. Real deployment should also confirm frost-pocket and hail frequency, slope stability and terrace drainage, and market and cold-chain linkages for perishable flowers and vegetables and should finalise array geometry with a coupled energy-yield and agronomy model. Weightings should be revisited with the grower if priorities (for example, retaining cereal selfsu iciency or maximising employment) di er from those inferred here.

Solar PV System Design Basis and Structural Assumptions

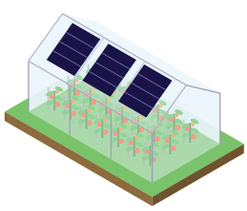
All PV energy yield simulations presented in this study are based on a uniform AgriPV structural and electrical configuration, applied consistently across all evaluated climatic zones (arid, semi-arid, tropical, continental,and temperate). This approach ensures that observed performance variations are attributable primarily to climate and irradiation characteristics, rather than design inconsistencies.

The standard structural parameters adopted for simulation are summarized and disclosed in the Technical Annex.

Elevated Agrivoltaics



Polyhouse Agrivoltaics



Vertical Agrivoltaics

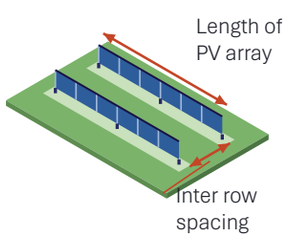


Table D29: Standard Structural Parameters Used in PVsyst[107]

Parameter	Specification	Design / Engineering Basis
Table configuration	4-panel portrait (4P)	High-density AgriPV layout enabling agricultural access
Mounting orientation	Fixed tilt, south-facing (lat-adjusted)	Yield optimisation under AgriPV constraints
Tilt angle	9.1°	Optimised to balance solar yield, inter-row shading, and crop light transmission
Row pitch (centre-to-centre)	12.5 m	Defined in main report; ensures machinery access
Clear aisle width	~7.29 m	Row pitch minus table width (Estimated table width ~5.21 m Derived from module dimensions)
Ground Coverage Ratio (GCR)	30-50% (Realistic number for AgriPV may vary)	Land-use optimisation for AgriPV
Light Transmission Ratio (LTR)	~24.7%	Inherent to GCR; light available to crop zone
Front edge height[108]	~3.5 m above ground	Satisfies agricultural machinery clearance
Rear edge height	~5.0 m above ground	Enhances airflow and bifacial rear-side capture
Height differential	~1.5 m	Improves ventilation and self-shading control

107 The results are indicative and may vary based on site location, latitude, climatic conditions, solar resource availability, system design, and operating conditions, cropping mechanism and crop yield.

108 May not be practical due to wind tolerance and structure strength and project cost economics. The system height is usually max 3-3.5 m

Table D29: (continued) Standard Structural Parameters Used in PVsyst

Parameter	Specification	Design / Engineering Basis
Structural material	Hot-dip galvanised steel (assumed)	O&M durability; corrosion protection
Foundation type	Driven piles (assumed)	Site-specific verification required
Agricultural access clearance	~ 3.5 m	Compatible with standard tractors and implements

System Comparison – Temperate Zone

Table D30: System Comparison for Temperate Zone — Jahu, Himachal Pradesh

Parameter	Elevated AgriPV System	Polyhouse-Integrated PV	Vertical PV System
Climatic stability	High	High	High
Temperature losses	Low	Low–Moderate	Low
Soiling losses	Low	Low	Very low
Bifacial gain	Medium	Low	Negligible
Long-term reliability	High	High	High
Design optimisation flexibility	High	Medium	Low
Specific generation (kWh/kWp)[109]	~ 1478 kWh/kWp/year		~978 kWh/kWp/year
Advantages of the system	• Stable irradiation and low thermal losses • Consistent bifacial contribution • High system reliability and lifespan	• Excellent integration with high-value agriculture • Stable PV operating conditions	• Very low maintenance requirements • Minimal crop shading
O&M aspect in the system	• Standard preventive maintenance regime • Long-term performance and degradation monitoring • Periodic structural inspections	• Routine electrical inspections within dual-use structures • Moderate corrosion monitoring • Coordinated agricultural and PV maintenance	• Low-intensity O&M requirements • Alignment and mounting verification • Periodic inverter and electrical checks

109 Specific generation values are reference figures derived from selected case studies and may vary across locations. Actual performance depends on local solar irradiance, climatic conditions, system configuration, and ground albedo, which is influenced by underlying soil properties, vegetation type, crop cover, and seasonal changes.

D4. Illustrative AgriPV system designing: Continental Zone — Grafschaft, Rhineland-Palatinate, Germany

Executive Summary

This study applies the project's crop-selection methodology to a 5.0-hectare arable parcel on the Grafschaft Plateau, Ahrweiler district, RhinelandPalatinate, in the continental zone above the Ahr Valley. The continental setting inverts the logic of the arid and tropical sites: there is no chronic heat stress, no water scarcity and no super-saturating sunlight to correct. Instead, **light is the limiting resource** - under the cloud-dominated sky (55% of irradiance is di use.

Figure 42: Continental zone illustrative site highlighted on map



Following the framework, a long list of crops from the region's industrial arable and horticultural systems was compiled, screened against the technical prerequisites, and the survivors scored against eight weighted parameters re-calibrated to this site. Because sunlight is scarce, the weightings reward crops whose value comes from protection and high market price rather than from shade, and they reflect two features absent at the smallholder sites: a **highly mechanized** industrial farming system and a **high-wage labour market** in which labour intensity is a genuine cost.

Result. The finalists score in a tight band (350–375 / 500) — meaningfully lower than at the sunny sites, which itself quantifies the 'continental light squeeze': no crop gains much from shade here. **Berries / soft fruit** lead (high value plus the strongest response to hail, frost and rain protection), with **leafy salads and root/bulb vegetables** close behind, then **brassicas, dual-use grassland and herbs**. Critically, unlike the other sites there is **no crop to abandon**: the excellent local arable rotation (wheat, barley, rapeseed, sugar beet, potato) simply belongs under a **vertical** array rather than an overhead one.

Site Context and Key Constraints

The parcel is a 200 m × 250 m rectangle (5.0 ha / 50,000 m^2) at 50.5880°N, 7.0549°E on the Grafschaft Plateau above the Ahr Valley — a medium-sized holding by Rhineland standards. Its key characteristics, from the supplied site brief, are summarized below.

Table D31: Illustrative Site Details for Continental Zone — Grafschaft, Rhineland-Palatinate, Germany

Parameter	Detail
Climatic zone	Continental — temperate humid maritime-continental (Köppen Cfb); year-round precipitation with no true dry season; di use-light dominant.
Elevation	~250–280 m ASL (Grafschaft Plateau).
Temperature	Annual mean 9.5–10.5 °C. Summer (Jun–Aug) 18–20 °C mean, 25–32 °C peaks, occasional >35 °C heat waves; Winter (Dec–Feb) 0–3 °C mean, −5 to −15 °C extreme minima; 100–130 frost days/yr.
Precipitation	650–800 mm/yr, distributed year-round; slight summer maximum (Jun–Aug 65–80 mm/month); increasing summer drought events (2018, 2019, 2022); winter precipitation partly as snow (10–25 days/yr).
Wind	Prevailing westerly / south-westerly; mean ~3.5–4.5 m/s at 10 m; exposed plateau with gusts to 90–110 km/h in winter storms (Orkantief events).
Soil type & texture	Deep, fertile Luvisols / Cambisols on thick loess-loam (Pleistocene aeolian); silty loam to sandy silt loam (~20% clay, ~55% silt, ~25% sand). Among Europe's most productive soils, but highly compaction susceptible.
Growing seasons	Single main season Apr–Oct (frost-free ~180–200 days); winter crops (wheat, barley, rapeseed) overwinter Oct–Mar.
Farming system	Highly mechanised industrial arable + intensive horticulture; GPS-precision agriculture and Integrated Crop Management; structured multi-year rotation; 5.0 ha is medium-sized locally.
Key risks	The 'light squeeze' under persistent cloud; spring/summer hail; frost (100–130 days) and winter cold; storm wind (Orkantief); increasing summer drought; soil compaction on the loess.

What the site tells us about priorities

- **Light is the scarce resource:** Under the di use continental sky, midday PAR on an overcast day (600–800 µmol/m^2/s) is already at the light-saturation point of wheat and near that of sugar beet, so adding even 25% panel shade (dropping PAR to ~450–600 µmol) would push C3 crops below their productive threshold. Shade is therefore a liability, and the design must be far more conservative than in any sunny climate.
- The array's agricultural value shifts to **physical protection** (shielding high-value crops from hail, frost and heavy rain) functions that do not depend on intercepting light.
- The farming system is **industrial and highly mechanized**, so a crop's compatibility with machinery matters here in a way it never did at the smallholder sites.
- This is a **high-wage economy**, so labor-intensive crops carry a real cost penalty.

Methodology

The analysis follows the project's four-step cropselection process:

Table D32: Crop Selection Parameters and Process for Continental Zone — Grafschaft, Rhineland-Palatinate, Germany

Stage	What is done
1. Initial Longlist	Compile all crops currently cultivated or viable across the local climate and the region's arable and horticultural systems, without yet considering AgriPV constraints.
2. Technical Prerequisites Filter (Go/No-Go)	Screen every crop against two non-negotiables — shade tolerance and low-to-medium height. In this light-limited climate the shade test is applied strictly, and sun-loving arable crops are routed to the vertical configuration rather than eliminated.
3. Prioritization Matrix	Score each surviving crop from 1 (very poor fit) to 5 (excellent fit) against eight weighted parameters, using site-specific weightings. Weighted score = raw score × weightage (in percentage points), exactly as in Table 5.
4. Final Selection	Rank crops by total weighted score; the highest scorers form the recommended shortlist, read together with the configuration analysis.

Step 1 — Initial Longlist

Drawing on the region's industrial arable rotation and its established horticulture and soft-fruit sectors (the Ahr Valley is a noted fruit- and wine-growing area), the crops grown or viable in and around the site were compiled.

The bulk of the land carries a structured cereal / oilseed / root rotation; higher-value horticulture, berries and orchard fruit occupy smaller, intensively managed blocks.

Table D33: Long list of crops for Continental Zone — Grafschaft, Rhineland-Palatinate, Germany

Group	Crops on the longlist
Cereals	Winter wheat, winter barley, rye, oats, spelt, triticale, grain maize
Oilseed / industrial	Oilseed rape (rapeseed), sunflower, sugar beet
Root & tuber	Potato, sugar beet, fodder beet, carrot
Field & fresh vegetables	Cabbage, cauliflower, broccoli, kale, onion, leek, beetroot, celeriac, beans, peas
Leafy salads & greens	Lettuce, spinach, chard, rocket
Soft fruit / berries	Strawberry, raspberry, blueberry, blackcurrant, redcurrant, gooseberry
Orchard fruit & vines	Apple, pear, cherry, plum; grapevine (Ahr wine region)
Forage / grassland	Grass-clover ley, lucerne, silage grass (dual-use grazing)
Herbs / high value / other	Parsley, chives, mint, chamomile and other culinary / medicinal-aromatic herbs; asparagus, rhubarb

Step 2 — Technical Prerequisites Filter (Go / No-Go)

Each longlisted crop is screened against the two prerequisites — **shade tolerance** and **low-to-medium height**. Two site-specific points apply here. Because light is scarce, the shade test is strict: crops that arenear light-saturation under the di use sky (the sunloving arable staples) are marked **No-Go for an overhead array** — but they are not discarded, because they are ideal under a **vertical** array that leaves them in near-full light. Tall orchard trees fail the height test for standard panels but suit purpose-built elevated protective structures

Table D34: Crops screening framework for Continental Zone — Grafschaft, Rhineland-Palatinate, Germany

Crop	Shade tolerance	Height	Verdict	Rationale
Winter wheat / barley / rye	Low–Med	Medium	**No-Go (overhead)**	C3 cereals are already near light-saturation under the di use sky; overhead shade cuts yield. Excellent under a vertical array.
Oilseed rape (rapeseed)	Low	Medium–tall	**No-Go (overhead)**	Sun-loving; flowering needs full light. Suits vertical inter-rows.
Sugar beet	Low–Med	Low	**No-Go (overhead)**	Light-limited root crops near saturation; shade reduces sugar yield. Suits vertical; fully mechanised.
Potato	Low–Med	Low–medium	**No-Go (overhead)**	Sun-loving; better in vertical inter-rows (as in the Fraunhofer Heggelbach trial).
Grain maize / sunflower	Low	Tall	**No-Go**	Tall and sun-loving; height and light both conflict with panels.
Orchard fruit (apple, pear, cherry)	Med	Tall trees	**No-Go (standard)**	Height incompatible with standard panels, but ideal under purpose-built elevated protective fruit-AgriPV (see §8.1).
Berries / soft fruit (strawberry, raspberry, blueberry, currant)	Med	Low–medium	**Go**	High value; benefit strongly from rain, hail and frost protection; tolerate light shade. The standout protection-responsive crop.
Leafy salads & greens (lettuce, spinach, chard)	High	Low	**Go**	Shade-tolerant, high-value, fast; validated under bifacial arrays (Heggelbach lettuce).
Brassicas (cabbage, cauliflower, broccoli, kale)	Med–High	Low	**Go**	Cool-season, shade-tolerant, established field vegetables.
Root & bulb vegetables (carrot, onion, beetroot)	Med	Low	**Go**	Shade-tolerant, storable and highly mechanisable — a good fit for the industrial equipment base.
Grassland / forage (grass-clover ley, lucerne)	High	Low	**Go**	Very shade-tolerant; dual-use grazing (the Next2Sun grassland model); rebuilds compacted loess and fixes nitrogen.

Table D34: (continued) Crops screening framework for Continental Zone — Grafschaft, Rhineland-Palatinate, Germany

Crop	Shade tolerance	Height	Verdict	Rationale
Herbs & medicinal / aromatic plants	High	Low	**Go**	Shade-tolerant, high-value culinary and medicinal herbs.
Asparagus / rhubarb	Med	Low–medium	**Go (cond.)**	Perennial, high value; tolerate light shade; match the long life of the PV asset.

Outcome of the filter. Six finalists were carried into full scoring, representing the crops worth growing under an overhead array here: **berries, leafy salads & greens, root & bulb vegetables, brassicas, grassland / forage and herbs**. The entire sun-loving arable rotation (wheat, barley, rapeseed, sugar beet, potato, maize) is retained for the vertical configuration, and orchard fruit for elevated protective structures — both addressed in Section 8.

Step 3 — Prioritization Matrix

Weighting rationale: The framework instructs users to adjust the weightage column to the project's goals. Theweightings below are re-calibrated to a light-limited, mechanized, high-wage continental site. The main changes from the illustrative defaults are: **Resilience to Climate Change raised to 30%** (physical protection — hail, frost, rain — is the array's core agricultural value here); **Water & Irrigation Needs cut to 5%** (no water scarcity, only occasional summer drought); **Ease of Mechanization raised to 10%** (an industrial, GPSprecision farming system); and **Labour Intensity raised to 10%** (in a high-wage economy, labour-hungry crops carry a real cost). **Level of Demand / Value stays high at 25%** (only high-value crops justify the structure), and Crop Rotation is held at 10% to reward soil-building leys on the compaction-prone loess. Weights sum to 100%.

Table D35: Customized Weighting Rationale for Crop Selection Based on Site-Specific Constraints for Continental Zone — Grafschaft, Rhineland-Palatinate, Germany

Parameter	Weight	Rationale (site-specific)
Resilience to Climate Change	**30%**	Raised, and re-interpreted. With shade a liability, the array's value is physical protection — hail defence, frost bu ering, rain management — plus bu ering the increasing summer droughts and storm wind. This is the site's central value proposition, so it carries the top weight.
Ease of Mechanization	**10%**	Raised. The farm runs GPS combines, beet lifters and precision applicators; a crop's compatibility with mechanised operations genuinely matters on this industrial parcel.
Water & Irrigation Needs	**5%**	Lowered. Rainfall is adequate and year-round with no dry season; water demand barely discriminates (occasional summer drought aside).
Crop Rotation & Intercropping	**10%**	The deep loess soils are highly compaction-susceptible; nitrogen-fixing leys and structured rotation that restore soil structure are valuable, though the top perennial crops sit outside the arable rotation.
Labour Intensity	**10%**	Raised. In a high-wage labour market, labour-intensive crops (notably hand-picked berries) carry a real and distinctive cost penalty.
Lifespan of the Crop	**5%**	Short annuals give flexibility, but perennials (berries, orchard, leys) usefully match the 20–25-year life of the PV asset; a mild factor either way.

Table D35: (continued) Customized Weighting Rationale for Crop Selection Based on Site-Specific Constraints for Continental Zone — Grafschaft, Rhineland-Palatinate, Germany

Parameter	Weight	Rationale (site-specific)
Level of Demand (Value)	**25%**	Only high-value output justifies an AgriPV structure over plain ground-mount PV, so market value remains a top criterion.
Area Under Cultivation	**5%**	Market access and supply chains are strong across the German/European market regardless of a crop's regional scale, so this signals little.
Total	**100%**	

Scoring (1 = very poor fit … 5 = excellent fit): Each finalist is scored against every parameter on the 1–5 scale, based on the research.

Step 3 — Prioritization Matrix (scoring): Scores 1–5. The bottom row is the total weighted score (Σ score × weight), out of 500. Note the tight, relatively low band (350–375): with shade a liability rather than an asset, no crop scores as highly as the best crops at the sunny sites (405–415) — this gap is the 'continental light squeeze' made numerical.

Table D36: Crop prioritization scoring matrix for Continental Zone — Grafschaft, Rhineland-Palatinate, Germany

Parameter	Wt %	Berries	Leafy greens	Root & bulb veg	Brassicas	Grassland / forage	Herbs & MAPs
Resilience to Climate Change	30	5	4	3	4	3	4
Ease of Mechanization	10	2	3	5	3	5	3
Water & Irrigation Needs	5	3	3	4	3	5	4
Crop Rotation & Intercropping	10	2	4	4	4	5	3
Labour Intensity	10	1	2	5	3	5	2
Lifespan of the Crop	5	3	5	4	4	3	3
Level of Demand (Value)	25	5	4	3	3	2	4
Area Under Cultivation	5	4	4	5	5	5	3
Total Weighted Score	**100**	**375**	**370**	**370**	**355**	**355**	**350**

Step 4 — Final Selection and Ranked Shortlist

Ranking the six finalists by total weighted score gives the shortlist below. The band is deliberately narrow — a direct consequence of the light limitation, which capshow much any crop can gain under an overhead array here.

Table D37: Final list of crops shortlisted for Continental Zone — Grafschaft, Rhineland-Palatinate, Germany

Rank	Crop	Score /500	Why
1	**Berries / soft fruit (strawberry, raspberry, blueberry, currant)**	**375**	Highest value and the strongest response to physical protection — rain covers prevent Botrytis and fruit cracking, and hail and frost defence protect the crop. It's one real drawback is heavy hand-labour, which the high-wage setting penalises; that alone keeps its lead narrow.
2	**Leafy salads & greens (lettuce, spinach, chard)**	**370**	Genuinely shade-tolerant, high-value and fast, with several cycles a season; validated under bifacial arrays. Perishability and moderate labour temper it.
2	**Root & bulb vegetables (carrot, onion, beetroot)**	**370**	The best mechanisation and labour profile of the set — a natural fit for the industrial equipment base — and storable, though of moderate unit value.
4	**Brassicas (cabbage, cauliflower, broccoli, kale)**	**355**	Robust, shade-tolerant cool-season vegetables that sit neatly in the arable rotation; moderate value.
4	**Grassland / forage (grass-clover ley)**	**355**	Very tolerant, low-input dual-use option (grazing under panels) that rebuilds compacted loess; its low market value is the only thing holding it back.
6	**Herbs & medicinal / aromatic plants**	**350**	High value and shade-tolerant, but a smaller market niche and hand-labour needs place it last of the six.

Recommended primary shortlist: berries / soft fruit, with leafy salads and root/bulb vegetables as the highvalue horticulture core, brassicas and dual-use grassland for the rotation and soil, and herbs as a premium niche. But the more important conclusion is structural: because the scores are close and shade is aliability, the **configuration choice (Section 8) carries more weight than the crop choice** — the arable rotation should stay under a vertical array, and the highvalue protection crops belong under elevated structures.

Crop Recommendations by AgriPV Configuration

At this light-limited site the configuration is the primary decision. The three options are compared below and then discussed in turn, tailored to the Grafschaft parcel.

Table D38: Comparison of Crop Suitability Across AgriPV System Configurations for Continental Zone — Grafschaft, Rhineland Palatinate, Germany

Configuration	Light / shade regime	Recommended crops (this site)	Key rationale
Elevated (overhead)	Partial shade beneath panels — but the ground-coverage ratio must be kept LOW / high-transparency to avoid the light squeeze.	**Berries / soft fruit and orchard fruit (apple, pear, cherry); secondarily shade-tolerant leafy greens, brassicas, herbs.**	The value is physical protection — hail, frost and rain — not shade. Best reserved for high-value fruit that pays for the structure, as at the operating apple-orchard AgriPV pilot in Gelsdorf, Rhineland-Palatinate.
Vertical (bifacial, E/W-facing)	Near-full sunlight in the wide inter-row strips — no shade penalty, which is decisive in a light-limited climate.	**The full mechanised arable rotation: winter wheat, barley, rye, rapeseed, sugar beet, potato, plus grassland / grazing.**	The default recommendation here. It keeps the industrial rotation in near-full light while adding power (the proven German 'Next2Sun' model), fully accommodates GPS machinery between rows, shelters the exposed plateau from storm wind, and its E/W generation profile matches morning and evening demand.
Polyhouse (semi-transparent roof PV, LOW cover ratio)	Controlled climate with partial roof shading; PV cover must stay light because the light squeeze applies indoors too.	**Premium protected berries, salads and herbs; season extension and frost exclusion.**	Extends the short season and excludes frost, hail and rain for high-value protected crops, but in this climate the roof can carry only limited PV before crop light su ers — so energy yield per m^2 is constrained. Best as a small premium unit.

Elevated (overhead) AgriPV — reserved for highvalue protected fruit

- An elevated array places panels above the crop, but at this site it comes with a strict caveat: because sunlight is already scarce under the di use sky, the **ground-coverage ratio must be kept low and the layout as transparent as possible**, or the array will push light-demanding crops below their productive threshold. Given that constraint, elevated structures earn their keep only where the **physical protection is itself highly valuable** — that is, over high-value fruit. This is exactly the European 'fruit-voltaics' model: the panels take the place of the hail nets and rain covers already used over berries and orchard† fruit, cutting fungal disease, fruit cracking, hail damage and frost, while generating power. The recommended elevated crops are therefore **berries / soft fruit and orchard fruit (apple, pear, cherry)**, with shade-tolerant leafy greens, brassicas or herbs as understorey options at low coverage. The approach is already proven in the site's own region at the **Gelsdorf apple-orchard AgriPV pilot (Rhineland-Palatinate)**, and by commercial providers such as BayWa r.e. and SunFarming.

Vertical (bifacial) AgriPV — the default for the arable land

- Vertical bifacial panels stand in east/west-facing rows, occupying only a few centimetres of ground each, with wide (roughly 10–13 m) crop strips between them that receive **close to full sunlight**. In a light-limited climate this is the decisive advantage: there is essentially **no shade penalty on the crop**, so the entire mechanised rotation — winter wheat, barley, rye, rapeseed, sugar beet, potato — and grassland can continue almost unchanged while the array generates power. This is the established German model: Next2Sun's vertical systems (Europe's largest at Donaueschingen-Aasen, and further sites such as Lö ingen growing spelt, oats and buckwheat with cattle grazing between rows) show stable crop yields alongside strong generation, and Fraunhofer ISE's arable-AgriPV research (VAckerPower; DIN SPEC 91434, Category II) is built around them. Three further features fit this exposed plateau: the rows **accommodate GPS combines and beet lifters** in the wide alleys, they act as windbreaks against the 90–110 km/h Orkantief storm gusts, and the east/west orientation spreads generation across the **morning and evening demand peaks**. For the bulk of this 5-ha parcel, vertical is the primary recommendation.

Polyhouse / greenhouse-integrated AgriPV

- A polyhouse with semi-transparent roof PV gives a controlled environment for premium protected crops — berries, salads and herbs — and is valuable here for **season extension and frost exclusion** across the 100–130 frost-day winters, as well as hail and rain protection. The important constraint is that the **light squeeze applies indoors too**: under the clouddominated sky the roof can carry only a limited PV cover ratio before it starves the crop of light, so the achievable energy yield per square metre is lower than in a sunny climate. A polyhouse is therefore best deployed as a **small, high-value unit** for protected berries, exotic salads and herb production rather than as the main energy generator, and its economics lean more on premium o -season produce than on electricity.

Crop-Specific Rationale and Implementation Notes

- **Berries / soft fruit (top pick):** Strawberry, raspberry, blueberry and currant are the flagship crops of European fruit-AgriPV. A panel roof performs the job of the rain covers and hail nets these crops already use — cutting Botrytis and other fungal disease, preventing fruit cracking, and bu ering frost — while the crop's high market value comfortably supports the structure. The key watch-point is labour: handharvesting is expensive in this high-wage economy, which is exactly why berries' matrix lead is narrow; pick-your-own, semi-mechanised harvest, or a focus on the premium fresh market help. As perennials, berries also usefully match the 20–25-year life of the PV asset.

- **Leafy salads and root / bulb vegetables (corunners-up):** Leafy salads (lettuce, spinach, chard) are genuinely shade-tolerant, high-value and fast, giving several cycles a season — Fraunhofer's Heggelbach trial validated lettuce (with potato) under 5-m bifacial panels, reaching a land-equivalent ratio of about 1.6. Root and bulb vegetables (carrot, onion, beetroot) score highest of the finalists on mechanisation and labour, fitting the farm's industrial equipment base, and store well. Together they form the practical high-value horticulture core under a low-coverage elevated array.

- **Brassicas, grassland and forage:** Brassicas (cabbage, cauliflower, broccoli, kale) are robust, shade-tolerant cool-season vegetables that slot into the rotation. Grassland and grass-clover leys are the low-input dual-use option — grazing beneath the panels (the Next2Sun grassland model) while nitrogen-fixing leys rebuild the compaction-prone loess — and although their market value is low, they are the easiest and most soil-friendly land use under an array.

System design pointers for this site

- Minimise shade above all: prefer a vertical array for arable land and keep any elevated array to a low ground-coverage ratio with high light transmission — over-shading is the primary risk in this climate.
- Design the array for protection value: over high-value fruit, position and space panels to maximise hail, frost and rain-splash defence (the paying function here), effectively integrating the roles of a hail net and rain cover.
- Engineer for wind: the exposed plateau sees 90–110 km/h Orkantief gusts, so specify robust racking (as in Next2Sun's multi-module vertical designs) and use vertical rows as windbreaks.
- Protect the loess soil: deep, fertile but compactionprone soils need controlled tra ic layouts, minimal ground disturbance during construction, and grassclover leys in rotation to maintain structure.
- Accommodate the machinery: set row spacing and clearance for GPS combines, beet lifters and precision applicators, following DIN SPEC 91434 (Category I elevated, Category II vertical).
- Confirm grid access early: grid-connection capacity is a widely reported bottleneck for German AgriPV and can determine project viability as much as the agronomy.

Limitations. This is a desk study using an illustrative parcel; scores are expert judgements on a 1–5 scale and are approximate. The defining caveat is the reverse of the arid sites: because light is the limiting resource, **over-shading is the principal risk**, so a vertical or lowcoverage design and a one-to-two-season on-site trial are essential, and the deliberately lower absolute scores here should be read as a signal that AgriPV value at this site comes from protection, dual use and the energy yield rather than from crop-shade synergy. Real deployment should confirm grid-connection capacity (often decisive in Germany), array wind and structural loading, machinery clearances, and market and labour arrangements for any high-value fruit and should size the system with a coupled energy-yield and agronomy model. Weightings should be revisited with the grower if priorities (for example, maximising renewable generation versus protecting a specific high-value crop) di er from those inferred here.

Solar PV System Design Basis and Structural Assumptions

All PV energy yield simulations presented in this study are based on a uniform AgriPV structural and electrical configuration, applied consistently across all evaluated climatic zones (arid, semi-arid, tropical, continental, and temperate). This approach ensures that observed performance variations are attributable primarily to climate and irradiation characteristics, rather than design inconsistencies.

The standard structural parameters adopted for simulation are summarized and disclosed in the Technical Annex.

Table D39: Standard Structural Parameters Used in PVsyst Simulations[110]

Parameter	Specification	Design / Engineering Basis
Table configuration	4-panel portrait (4P)	High-density AgriPV layout enabling agricultural access
Mounting orientation	Fixed tilt, south-facing (lat-adjusted)	Yield optimisation under AgriPV constraints
Tilt angle	9.1°	Optimised to balance solar yield, inter-row shading, and crop light transmission
Row pitch (centre-to-centre)	12.5 m	Defined in main report; ensures machinery access

110 The results are indicative and may vary based on site location, latitude, climatic conditions, solar resource availability, system design, and operating conditions, cropping mechanism and crop yield.

Table D39: (continued) Standard Structural Parameters Used in PVsyst Simulations

Parameter	Specification	Design / Engineering Basis
Clear aisle width	~7.29 m	Row pitch minus table width (Estimated table width ~5.21 m Derived from module dimensions)
Ground Coverage Ratio (GCR)	30-50% (Realistic number for AgriPV may vary)	Land-use optimisation for AgriPV
Light Transmission Ratio (LTR)	~24.7%	Inherent to GCR; light available to crop zone
Front edge height	~3.5 m above ground	Satisfies agricultural machinery clearance
Rear edge height[111]	~5.0 m above ground	Enhances airflow and bifacial rear-side capture
Height differential	~1.5 m	Improves ventilation and self-shading control
Structural material	Hot-dip galvanised steel (assumed)	O&M durability; corrosion protection
Foundation type	Driven piles (assumed)	Site-specific verification required
Agricultural access clearance	≥ 3.5 m	Compatible with standard tractors and implements

System Comparison – Continental Zone

Table D40: System Comparison for Continental Zone — Grafschaft, Rhineland-Palatinate, Germany

Parameter	Elevated AgriPV System	Polyhouse-Integrated PV	Vertical PV System
Seasonal variability	High	Moderate	High
Winter performance	Reduced	Moderated by structure	Relatively improved
Snow impact	Manageable	Potential accumulation	Minimal
Annual PR stability	High	Medium	Medium
Bifacial rear gain	Medium (seasonal)	Low	Negligible
Structural complexity	Moderate	High	Low
Specific generation	1071 kWh/kWp/year		~847 kWh/kWp/year

111 111 May not be practical due to wind tolerance and structure strength and project cost economics. The system height is usually max 3-3.5 m

Table D40: **(continued) System Comparison for Continental Zone — Grafschaft, Rhineland-Palatinate, Germany**

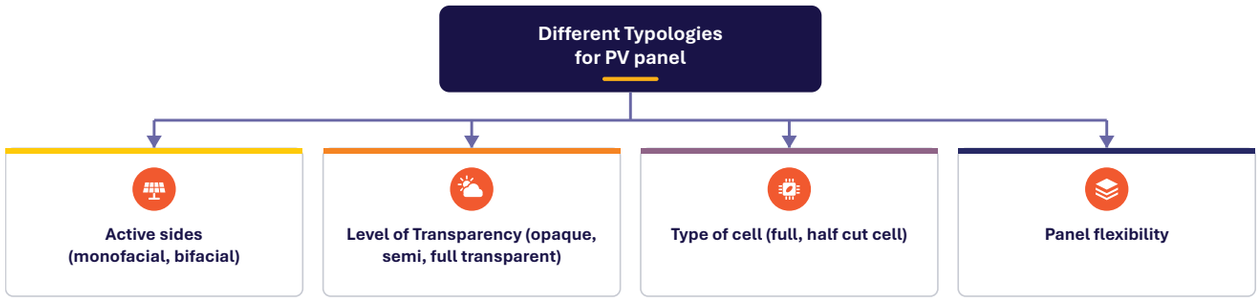
Parameter	Elevated AgriPV System	Polyhouse-Integrated PV	Vertical PV System
Advantages of the system	• Strong summer performance with effective cooling • Snow shedding possible with low tilt • Stable long-term PR	• Internal thermal bu ering improves winter crop productivity • Reduced snow exposure on modules	• Better winter performance at low sun angles • Minimal snow accumulation
O&M aspect in the system	• Seasonal maintenance planning for summer and winter conditions • Snow and frost inspection where applicable • Monitoring seasonal performance variation	• Structural checks for snow load accumulation • Ventilation adjustments during warmer months • Inspection of integrated roof components	• Minimal snow accumulation on module surfaces • Anchorage inspections following freeze–thaw cycles • Winter generation performance tracking

Appendix E – Cost Components & Assumptions

Innovative PV panel typologies for AgriPV system

The continuous evolution of PV panel technology, particularly the shift towards n-type architectures and advanced cell designs, promises further e iciency gains and cost reductions, making solar PV an increasingly viable and attractive solution for both energy generation and integrated agricultural applications. The operational advantages of different PV panel types are discussed in this subsection with context of installation in an AgriPV system. The different typologies are

Figure 43: Di erent Typologies for AgriPV Panels



- The strategic selection of PV panel types in AgriPV should be guided by the specific requirements of both the energy and agricultural components of the system.
- Bifacial panels and half-cut cell designs promise enhanced energy capture and resilience under partial shading
- Semi-transparent panels resolve the need for sunlight for energy generation and for crop growth by allowing light transmission through panels.
- Glass-on-glass panels provide robust durability essential for long-term outdoor use.
- Flexible panels expand design possibilities on unconventional surfaces.
- A **well-considered mix** of these typologies can optimize land use, balance energy production with agricultural yield, and ensure operational reliability across diverse environmental conditions.

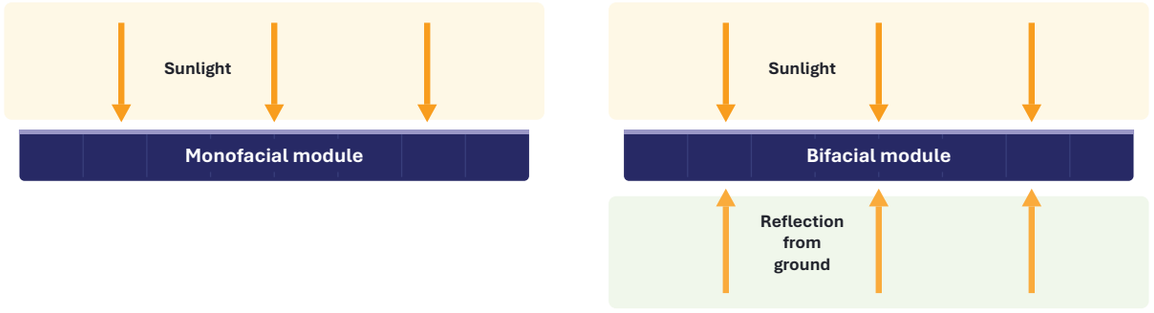
Monofacial and Bifacial panels

Monofacial panels utilize sunlight for energy generation from front surface of panel only. Monofacial panels are well-understood amongst the project developers with established installation protocols.

Bifacial panels utilize sunlight for energy generation from both the front and rear surfaces of the panel. These panels are increasingly being adopted by project developers for installation.

The illustration of monofacial and bifacial panels is shown in Figure 44.

Figure 44: Monofacial and bifacial panels

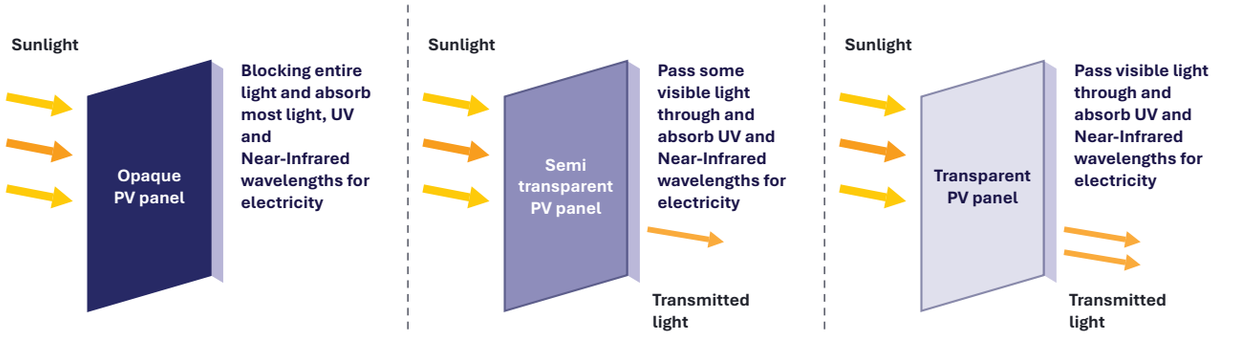


The rear surface of the bifacial panel generates energy from the ground-reflected di used light. In context of AgriPV, there is higher reflected di used light in comparison with bare soil on ground due to presence of crops73 underneath the panels. This results in higher energy generation from bifacial panels.

Semi-transparent and transparent Panels

Semi-transparent and transparent PV panels provide a way to generate energy while allowing some light to pass through. These panels have been adopted primarily in building integrated PV applications where they allow effective architectural integration while allowing energy generation as well. AgriPV light transmission through different levels of transparency in solar panels is shown in Figure 45.

Figure 45: Light transmission through opaque, semi-transparent, and transparent panels



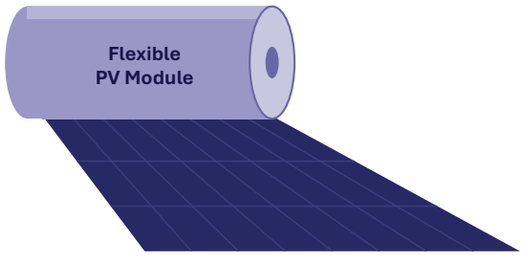
Semi-transparent panels are usually designed by increasing the spacing between crystalline silicon solarcells in the glass-on-glass panel (silicon cells laminated between glass) though this reduces the power capacity per unit area of the panel. Other ways of designing semitransparent panels include thinning of photovoltaic layer that is possible with PV technologies such as thin film technology (amorphous silicon, Cadmium Telluride), and organic PV technology74 . Bifacial panels by design (due to space between cells, glass-on-glass panel structure) are semi-transparent. Thin film panels can be both monofacial and semi-transparent.

Transparent PV panels are designed using advanced technologies such as thin film technology, organic PV technology, dye-sensitized solar cells, and perovskite solar cells75 . These panels have lower e iciency than crystalline silicon panels. Hence transparent panels require more surface area for generating same power as crystalline silicon panels. The ability to maintain a luminous environment underneath the transparent panels allow for effective crop production in context of AgriPV.

Flexible Solar Panels

Flexible solar panels are photovoltaic panels fabricated using lightweight and pliable materials, enabling theirconformation to curved surfaces and unconventional architectural designs. Flexible panel is illustrated in Figure 46.

Figure 46: Flexible PV panel



Unlike rigid solar panels, flexible panels often leverage thin-film technologies, including Copper Indium Gallium Selenide (CIGS), Cadmium Telluride (CdTe), amorphous silicon (a-Si), perovskite, and organic solar cells. Their inherent adaptability facilitates integration into diverse and unconventional AgriPV structures, such as curvilinear polyhouse roofs or tensile shade structures, thereby o ering novel design possibilities and optimizing land use e iciency.



CONTACT US
International Solar Alliance
Surya Bhawan, National Institute of Solar Energy Campus
Gwal Pahari, Faridabad-Gurugram Road, Gurugram
Haryana – 122003, India
Email: info@isa.int | Website: www.isa.int