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Agrivoltaics: Harmonizing Renewable Energy Production with Sustainable Agriculture

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Abstract:

Agrivoltaics represents a transformative convergence of renewable energy production and sustainable agricultural practice, in which solar photovoltaic (PV) systems are harmoniously co-located with crop cultivation on the same land unit. As the global population is projected to reach 9.8 billion by 2050, escalating pressures on food, energy, and water resources necessitate transformative solutions. Agrivoltaics addresses this Food-Energy-Water (FEW) nexus by exploiting the principle of light sharing — strategically placing elevated solar panels above crops to capture excess solar radiation beyond plants' light saturation point, generating clean electricity while simultaneously creating a protective microclimate. This review consolidates current evidence on the agronomic, technological, economic, and environmental dimensions of agro-solar farming. Key findings indicate that agrivoltaic systems can reduce crop water requirements by 20–50%, lower sub-canopy temperatures by 2–8°C, and achieve Land Equivalent Ratios (LER) of 1.3–1.84, signifying substantially superior combined land productivity over separate systems. The global agrivoltaic market, surpassing 5 GW capacity by 2024, is projected to exceed USD 10 billion by 2030. With an estimated agrivoltaic potential of 3,156–13,803 GW, India is promoting adoption through schemes like PM-KUSUM and SKY, making agrivoltaics a key technology for climate-resilient agriculture despite economic and regulatory challenges.

Keywords: Agrivoltaics, Sustainable Agriculture, Land Equivalent Ratio, Photovoltaic, Light Saturation Point, Food-Energy-Water Nexus, PM-KUSUM.

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1. Introduction

Agriculture and energy production have historically competed for land resources — two of humanity's most urgent needs locked in a zero-sum contest. Agrivoltaics — the deliberate co-location of solar photovoltaic (PV) systems and agricultural activities on the same parcel of land — offers a paradigm-shifting resolution to this conflict. The concept was first conceptualised by

Adolf Goetzberger and Armin Zastrow at Germany's Fraunhofer Institute in 1981, and practically demonstrated by Akira Nagashima in Japan in 2004 through his concept of "Solar Sharing," agrivoltaics has evolved from a theoretical curiosity to a globally scaling technology (Nagashima, 2004). Since then, it has rapidly evolved from niche pilot projects to a globally recognized Climate-Smart Agriculture (CSA) strategy.

The word 'harmonize' captures the essential promise of agrivoltaics — not a compromise between food and energy, but a genuine synergy where each system enhances the performance of the other. Solar panels moderate the crop microclimate while crops cool the panels; shading reduces water stress while the same land generates clean electricity. This review examines the scientific, technological, economic, and policy dimensions of this harmony.

The fundamental operating principle is Light Sharing. Most crops possess a biological "light saturation point" — a threshold beyond which additional photosynthetically active radiation (PAR, 400–700 nm) cannot be utilized for growth and instead causes heat stress and excessive transpiration. By strategically positioning solar panels above or between crop rows, excess light is captured for electricity generation while the panels simultaneously create a moderated, cooler microclimate — reducing water evaporation by up to 40–50% and shielding crops from extreme temperature events (Lokesh et al., 2024; Dupraz et al., 2011). This symbiotic relationship is further reinforced by the cooling effect of crop transpiration on panel surfaces, which can increase panel electricity generation efficiency by 1–3%.

According to the Food and Agriculture Organisation (FAO, 2018), Climate-Smart Agriculture (CSA) is an integrated approach that sustainably increases agricultural productivity, builds climate resilience, and reduces greenhouse gas emissions. Agrivoltaics satisfies all three pillars of CSA: it boosts productivity through dual-use land, enhances adaptation via microclimate modification, and contributes to mitigation by displacing fossil fuel-based electricity. The global agrivoltaic market is projected to exceed USD 10 billion by 2030, with installed capacity already surpassing 5 GW worldwide as of 2024 (GIZ, 2024).

2. System Components and Working Mechanism

Understanding how agrivoltaics achieves its dual-purpose harmony requires examining each component of the integrated system and the physical mechanisms through which energy and agricultural subsystems mutually reinforce one another. An agrivoltaic system is composed of five integrated subsystems, each critical to the dual-function output of electricity and food:

- **Solar PV Modules:** Bifacial modules (capturing light from both surfaces via the Albedo effect) and semi-transparent thin-film modules are preferred. Bifacial panels increase energy yield by 10–25% compared to conventional monofacial panels in raised setups.

- **Elevated Mounting Structures:** Steel or aluminium pillars raising panels 2.5–5.0 metres above ground, allowing tractor clearance and preventing heat entrapment beneath the array.
- **Inverters and Battery Storage:** Convert DC electricity to AC for on-site use (irrigation pumps, cold storage) or grid export under net-metering/feed-in-tariff mechanisms.
- **Monitoring and Sensing Systems:** Soil moisture sensors, pyranometers (light intensity meters), weather stations, and canopy temperature sensors enable precision management of both crop and energy subsystems.
- **Smart Irrigation and Self-Cleaning Modules:** Precision drip or fertigation systems integrated with automated panel-cleaning mechanisms that minimise water use while maintaining panel efficiency.

Working Mechanism — Light Sharing: The system exploits the biological light saturation point of crops (the threshold beyond which additional PAR causes heat stress rather than photosynthesis). Solar panels intercept this "excess" light for electricity generation, while allowing sufficient diffuse and transmitted PAR to reach the crop canopy below. Ground Coverage Ratios (GCR) in agrivoltaics are maintained at 30–50% (versus 60–70% in standard solar farms) to ensure adequate crop irradiation. A virtuous feedback loop is established: crops transpire water vapour, cooling the sub-panel microclimate; cooler panels operate more efficiently, generating up to 3% more electricity than panels over bare ground (Dinesh and Pearce, 2016). Panel temperatures can drop by 10–15°C compared to conventional ground-mount installation.

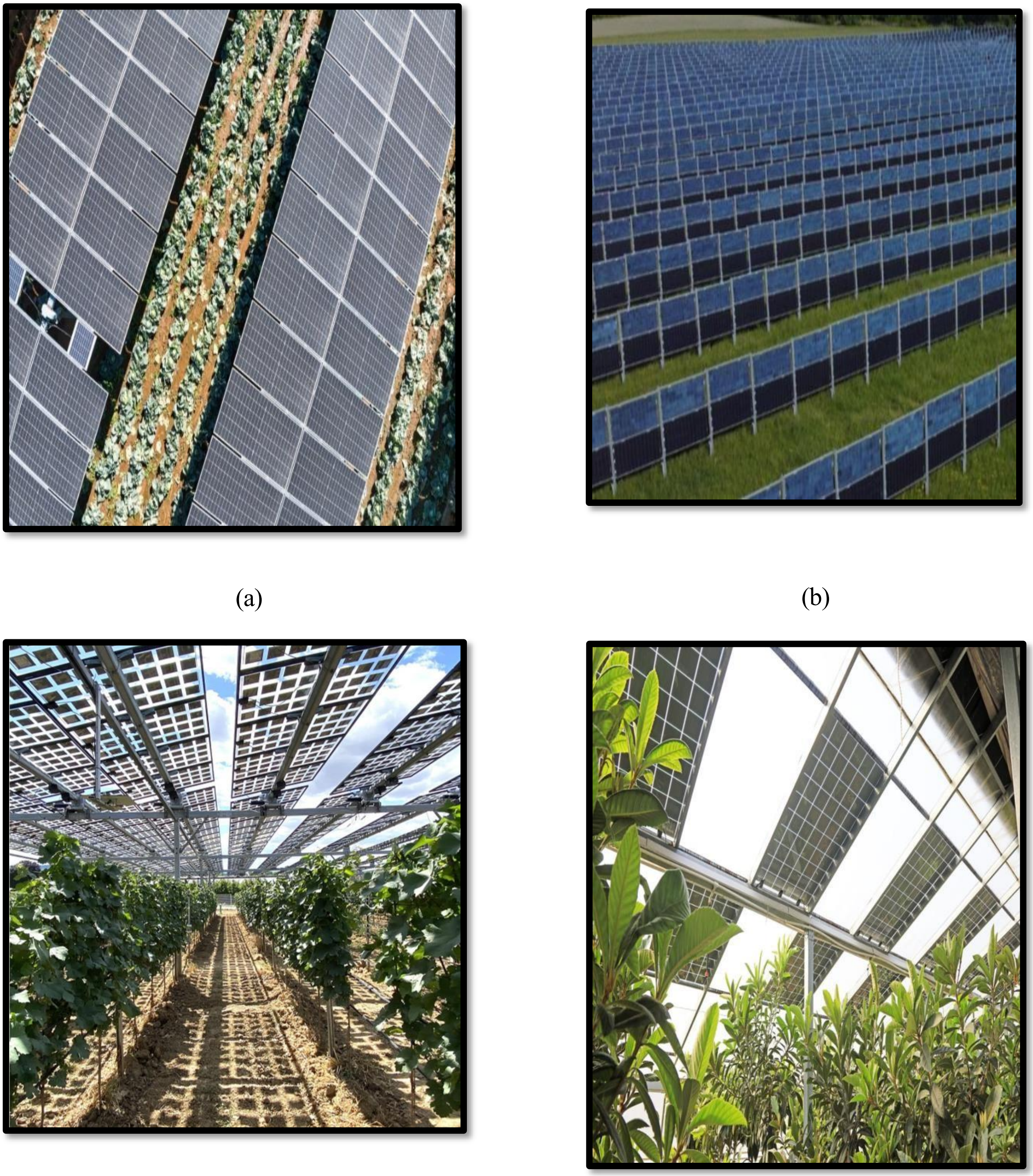
3. Types, Design and Technology

3.1 Major Agrivoltaic System Types

System Type	Configuration	Best Crop Fit	Key Advantage
Fixed Elevated /Overhead	Panels mounted on high stilts (2.5–5 m) with a spaced or checkerboard arrangement	Leafy greens, berries, fruit trees, livestock grazing	Maximizes land-use efficiency (LUE) and supports mechanized harvesting
Dynamic / Tracking	Panels tilt on single- or dual-axis systems with AI-controlled movement	Vineyards, high-value horticulture, orchards	Optimizes crop light availability and energy generation in real time

Vertical Bifacial	Upright fence-like bifacial panels arranged in north–south rows	Wheat, oats, maize, pasture grass	Allows full machinery access, reduces wind impact, and avoids overhead rain obstruction
Inter-row Farming	Conventional panels installed with widened spacing between rows for crop lanes	Sun-loving cereals such as wheat, maize, and rice	Uses standard ground-mounted panels, lowers installation cost, and remains mechanization-friendly
Greenhouse PV	Semi-transparent photovoltaic modules integrated into greenhouse roofs and walls	Tomatoes, cucumbers, flowers, controlled-environment horticulture	Enables year-round cultivation with self-powered climate control and urban adaptability

Table 1. Classification of agrivoltaic system types (Amaducci et al., 2018; Weselek et al., 2021)



(a) (b)

(c) (d)

Figure 1: Major Agrivoltaic system types (a) Fixed Elevated /Overhead system (b) Vertical Bifacial system (c) Inter-row Farming system (d) Greenhouse Photovoltaic system

3.2 Design Parameters

Optimal agrivoltaic design requires careful calibration of three primary physical parameters:

- Tilt Angle (20–25°): Panels are often set at shallower angles than latitude-optimal to allow more ground-level irradiation during critical crop growth stages. Dynamic single-axis trackers can rotate to vertical during heavy rain events, enabling full soil recharge.
- Row Spacing (Pitch): GCR of 30–50% is maintained. Row spacing (4–6 m between rows) is determined by farm machinery turning radius, ensuring safe tractor and harvester passage.
- Mounting Height (2.5–5 m): Provides tractor clearance, prevents thermal inversion under the array, and creates an adequate air buffer to moderate the sub-panel microclimate without over-shading.

3.3 Solar Cell Technologies for Agrivoltaics

Feature	**Monocrystalline**	**Polycrystalline**	**Thin-Film**	**Bifacial (Mono)**
Efficiency	19–22%	15–17%	10–13%	Up to 22%+
Durability	25–30 years	20–25 years	10–15 years	25–30 years
Heat Tolerance	Good	Fair	Best (stable)	Good
Best AV Use	Overhead elevated	Inter-row/Budget	Solar greenhouses	Vertical & high-yield
Visual	Uniform black	Speckled blue	Smooth/transparent	Glass-on-glass

Table 2. Comparison of solar cell types used in agrivoltaic applications (Mahmoud et al., 2025)

An important emerging technology is Spectral Splitting through Organic Photovoltaic (OPV) cells, which can be tuned to absorb wavelengths unused by crops (green light, UV, near-infrared) while transmitting the growth-critical red and blue PAR wavelengths. This represents the next frontier in light-use optimization within agrivoltaic systems (Modi et al., 2024).

4. Agricultural Aspects: Crops, Soil Health, and Microclimate

4.1 Crop Selection — Shade Tolerance Spectrum

Category	**Crop Examples**	**Notes**
Highly Suitable (Shade-Loving)	Lettuce, Spinach, Potatoes, Onions, Mushrooms, Ginger, Colocasia	Thrive under 20–50% shade; benefit most from microclimate cooling

Moderately Suitable	Tomatoes, Berries, Legumes (Green gram, Soybean — in interspaces), Cabbage	Yield comparable to open-field under well-designed inter-row systems
India-Specific HVCs	Aloe Vera, Medicinal plants, Saffron (Kashmir), Strawberries (MP), Herbs	High economic value; premium pricing offsets any yield reduction

Table 3. Crop suitability categories for agrivoltaic systems (Pawar et al., 2025)

4.2 Microclimate and Agronomic Benefits

The sub-panel microclimate is perhaps the clearest expression of the agrivoltaic harmony — a space where reduced radiation, buffered temperatures, and retained soil moisture collectively create growing conditions superior to open-field exposure for shade-tolerant species

- **Heat Stress Reduction**: Sub-panel air temperatures are 2–8°C lower than open-field conditions during peak summer, directly reducing crop heat stress and improving quality (Adeh et al., 2019).
- **Water Efficiency**: Shade reduces soil evaporation by 20–30%, cutting irrigation water requirements by 15–50% — critically important for India's water-stressed arid and semi-arid regions.
- **Soil Organic Carbon (SOC)**: Panel shading reduces soil temperatures by 5–10°C, slowing organic matter decomposition and promoting SOC accumulation.
- **Nutrient Retention**: Panels intercept heavy rainfall impact, reducing nutrient leaching and topsoil erosion. Field trials report higher N, P, and K levels in agrivoltaic plots compared to open-field controls (Giri and Mohanty, 2024).
- **Pest and Disease Management**: While increased humidity under panels can elevate fungal disease risk (root rot, powdery mildew), Integrated Pest Management (IPM) strategies — including resistant variety selection, strategic row spacing, precision monitoring, and biological control — effectively manage this risk.

5. Economics of Agrivoltaics Farming

The economic model of agrivoltaics is fundamentally a Dual-Revenue framework. While initial capital investment (CAPEX) is 15–30% higher than conventional ground-mount solar (due to elevated structures costing 50% more steel), the combined financial returns from electricity sales and crop production deliver substantially superior long-term economic performance.

Metric	**Traditional Farming**	**Agrivoltaic System**	**Key Advantage**
Annual Revenue	₹1.5–4 Lakh/ha (crop only)	₹25–40 Lakh (energy + crop)	~10× higher revenue
Payback Period	Seasonal (year-to-year)	4–7 years (with PM-KUSUM)	Guaranteed income
Annual ROI	2–8% (market-linked, variable)	12–16% (annual avg.)	Stable guaranteed income
Water Requirement	100% (high evaporation)	70–85% of baseline	15–30% water saving
Land Productivity	Baseline (1.0)	LER 1.3–1.84	60–84% more productive
Risk Profile	High (weather/market)	Low (guaranteed solar PPA)	Diversified income shield

Table 5. Economic comparison: Traditional farming vs. agrivoltaic dual-use systems (Wang and Chen, 2024)

The primary metric for evaluating agrivoltaic system productivity is the Land Equivalent Ratio (LER). The Land Equivalent Ratio (LER) is the mathematical expression of the agrivoltaic harmony: it quantifies the productive premium achieved when energy and food are co-produced on the same land compared to two separate systems.

LER = [Agricultural Yield (AV) ÷ Agricultural Yield (Monoculture)] + [Solar Yield (AV) ÷ Solar Yield (Conventional Solar)]

LER < 1.0 = Inefficient | LER = 1.0 = Neutral | LER > 1.0 = Productive (Dual-Use Advantage)

6. Indian Scenario

India's agrivoltaic potential is immense. A 2024 GIZ-Fraunhofer ISE report estimates a technical potential of 3,156–13,803 GW — far exceeding India's 500 GW renewable energy target. Critically, converting just 1% of India's cultivated land to agrivoltaics could generate over 600 GW of solar power while simultaneously preserving agricultural production.

6.1 Policy Framework

The Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan (PM-KUSUM) scheme, particularly Component A, encourages farmers to install decentralised solar power plants (up to 2 MW) on barren or fallow land, which are readily adaptable to agrivoltaic models. Key state-level initiatives include:

- Gujarat — Suryashakti Kisan Yojana (SKY): 60% subsidy for panel installation with a government buy-back rate of ₹7/unit for the first 7 years.
- Maharashtra — Mukhyamantri Saur Krishi Vahini Yojana: Target of solarising 30% of

agricultural feeders by 2025 through cluster farming hubs.

- I-SUN Project: Partnership between the Government of Germany (GIZ) and India's Ministry of New and Renewable Energy (MNRE) exploring innovative solar applications (NISA) to minimise land use.

6.2 Key Stakeholders

Several premier Indian institutions are driving agrivoltaic research and deployment:

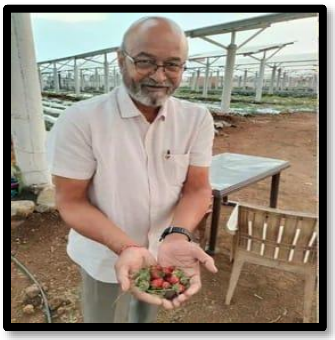
- National Institute of Solar Energy (NISE): R&D on crop-specific panel heights.
- ICAR: Identifying shade-tolerant indigenous crop varieties for diverse agro-climatic zones.
- Private Sector: Tata Power and Mahindra Susten exploring 'Vertical Solar Fencing' pilots in Punjab and Haryana.
- Anand Agricultural University (Gujarat): Collaborative research on agrivoltaic system performance for Kharif crops.

6.3 Notable Indian Success Stories

- **The "IITian's Organic Farm", Sagar, Madhya Pradesh:** India's largest private agrivoltaic plant (16 acres), developed by Anand Jain (IIT Roorkee alumnus). Panels mounted at 12–15 feet; crops include organic strawberries, broccoli, and lettuce. The farm generates 25,000 units of electricity daily — a prime example of Climate-Smart horticulture.

Meet The IITian Growing Organic Food Under India's Largest Agrivoltaic Solar Plant

In Madhya Pradesh, Anand Jain's 16-acre farm utilises agrivoltaics to produce crops and solar power without sacrificing arable land. This innovative dual-use technology provides a sustainable farming model and supplies about 25,000 units of electricity to the grid daily.



- **Amrol Distributed Solar Project, Anand, Gujarat:** 1 MW, 12-acre project by GIPCL and Anand Agricultural University. Tested groundnut, soybean, cotton, millet, wheat, and banana under partial shade. Proved Kharif crop viability under an agrivoltaic canopy and underpinned the SKY policy framework.

7. Barriers to Harmony: Challenges in Agrivoltaic Adoption

Despite significant promise, agrivoltaic adoption faces several interconnected barriers that must be addressed through technical innovation, policy reform, and financial instruments:

- **High Initial CAPEX:** Elevated agrivoltaic systems are 15–30% costlier than conventional solar setups, limiting affordability for small farmers.

- **Technical Complexity:** Systems require crop- and site-specific designs based on shading, machinery, and microclimate conditions.
- **Regulatory Gaps:** Lack of clear agrivoltaic land-use policies in India creates permitting and insurance challenges.
- **Equipment Damage Risk:** Farm machinery may accidentally damage mounting structures or solar panels during field operations.
- **Long-term Liability:** Long-term solar agreements often conflict with shorter agricultural planning cycles.
- **Rainwater Runoff:** Panel structures can concentrate rainfall at edges, causing uneven soil moisture and erosion.
- **Microclimate Pathogens:** Higher humidity and lower airflow under panels may increase fungal disease incidence.

8. The Future of Harmony: Emerging Technologies and Pathways

The future of agrivoltaics is being shaped by rapid advances in precision technology, materials science, and digital agriculture:

- **AI-Driven Agrivoltaics:** AI-based systems will optimize panel angles in real time using crop and sensor data to balance energy production and plant growth.
- **Organic Photovoltaics (OPV):** Flexible "smart shade" solar films will allow photosynthesis while generating electricity, reducing installation costs.
- **Autonomous Robotics:** Electric autonomous tractors will reduce labour needs and minimize machinery damage risks in agrivoltaic farms.
- **Harmonized Land-Use Policies:** Governments and the FAO are developing unified policies that officially recognize agrivoltaic land as a dual-use category for both agriculture and energy production.
- **Aquavoltaics:** Floating solar panels over fish ponds can reduce water evaporation and algal growth while producing clean energy.
- **Policy & Standardization:** Emerging design standards and supportive policies will simplify regulations and encourage wider adoption.
- **Integrated Food-Energy-Water Hubs:** Future systems will combine solar irrigation, cold storage, and EV charging to create self-sustaining farm energy hubs.

9. Conclusion

Agrivoltaics achieves what competing land-use models cannot: a genuine harmony between renewable energy production and sustainable agriculture. It is not a trade-off, not a compromise, but a documented, measurable synergy validated across climates, crop types, and economic contexts. The LER values of 1.3–1.84 recorded across global trials are, in essence, the quantified dividend of that harmony.

For India — a nation of 140 million farm holdings confronting simultaneous climate vulnerability, energy poverty, and the world's largest renewable energy ambition — agrivoltaics could be the key to achieving the **500 GW renewable target** without compromising food security. With the PM-KUSUM framework, state-level SKY schemes, the GIZ I-SUN partnership, and pioneering domestic projects demonstrating commercial viability, the institutional foundations for scale-up are in place. Agrivoltaics could indeed be India's key to achieving its 500 GW renewable energy target without compromising its food security.

The future of food and energy need not be a zero-sum competition for land. Agrivoltaics proves that with intelligent design, these twin imperatives can be synergistically integrated — turning the fields of today into the power stations and food gardens of tomorrow.

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