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Beyond the Energy-Agriculture Binary: How Agriphotovoltaics Can Transform India's Rural Economy through PM KUSUM

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***Abstract:** India's agricultural subsidy regime presents a paradox: it reflects distorted power subsidies that incentivise unmetered groundwater pumping, leading to an overexploitation problem in many parts of India. Concurrently, India's transition to clean energy is gaining momentum toward the 500 GW target by 2030. Large-scale solar expansion through ground-mounted systems on farmland has provided energy opportunities at the cost of agricultural production, thereby creating land-use competition. This paper argues that Agriphotovoltaics (APV) can act as a strategic solution to transcend this false binary by enabling dual land use for both crop cultivation and solar generation. Drawing on two types of APV business models from Rajasthan and Delhi, this paper shows that farmer-centric APV models under PM-KUSUM Component A can yield returns per acre of 9-10 times those of conventional farming. However, developer-led models risk reducing farmers to passive landlords. Currently, in India, scaling APV models is being constrained by definitional ambiguities, inadequate financial instruments, and institutional fragmentation. We propose a four-pillar policy framework: farmer-centric technical specifications and technical standards, a better financial architecture through targeted capital subsidies, strengthening farmer-producer organisations to facilitate collective ownership models, and finally, region-specific agronomic research. Such a framework will ensure that APV becomes a mainstream livelihood solution, supporting energy security and the agricultural sustainability of Indian farmers.*

***Keywords:** Agriphotovoltaics, Feed-in Tariff, Farmers' income, Business Models, Renewable Energy*

Nomenclature:
HYV: High-Yielding Variety
GHG: Greenhouse Gas
SIP: Solar Irrigation Pump
IPS: Individual Pump Solarisation
ICRIER: Indian Council for Research on International Economic Relations
VGF: Viability Gap Funding
JVVNL: Jaipur Vidyut Vitran Nigam Limited
IRR: Internal Rate of Return
BSES: Bombay Suburban Electric Supply
FPO: Farmer Producer Organisation
SBI: State Bank of India
SEBs: State Electricity Board
SKY: Suryashakti Kisan Yojana
FiT: Feed-in-Tariff

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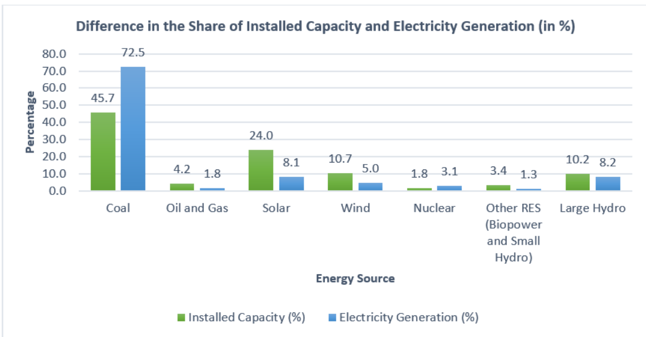
I. INTRODUCTION

India is at a pivotal juncture in its energy transition. By June 2025, the country's installed power capacity reached 484.2 GW, of which non-fossils account for ~243 GW1 (50%) of the total, with solar alone contributing ~116 GW. Yet a critical imbalance persists. From April 2024 to June 2025, coal dominated the power generation at ~73%, while solar, despite forming 24% of installed capacity, contributed only ~8% of actual generation [1]. This gap stems from grid integration challenges, including limited storage capacity, inadequate transmission infrastructure, and a mismatch between peak solar output and evening demand. Curtailment of solar power by DISCOMs, often due to financial stress or contractual rigidities, further reduces utilization. Seasonal variability and intermittency also hinder reliable supply without backup systems. Together, these issues create an imbalance in which coal continues to dominate generation despite Solar's rising share of capacity, slowing progress toward a cleaner, more diversified energy mix. Figure 1 shows the difference in the percentage share of the installed capacity and electricity generation of different energy sources in India's energy mix.



[Fig.1: Difference in the Share of Installed Capacity and Electricity Generation (%)]

Source: India Climate and Energy Dashboard (NITI Aayog)

India must reconcile its clean energy ambitions with its evolving agrarian economy. Over 60% of the country's land is under cultivation, making land-use competition between food and energy one of the most pressing policy challenges [2]. Agriphotovoltaics offers a strategic solution by enabling dual land use that produces solar power while sustaining and improving agricultural yields. By allowing farmers to earn a steady income from solar generation without abandoning cultivation, APV aligns energy transition goals with rural livelihood security.

The paper unfolds across six interconnected sections that build a comprehensive argument for APV as a solution to competing land-use demands when considered from the right approach. Section 2 traces the evolution of the water-energy nexus in agriculture from the Green Revolution era, examining how this relationship has generated both beneficial and detrimental externalities. It then explores a critical contemporary paradox: renewable energy strategies designed to mitigate climate vulnerabilities in agriculture are inadvertently displacing agricultural production itself. The section concludes by proposing dual land use as a viable resolution within existing policy frameworks.

Building on this further, Section 3 presents APV as a paradigmatic solution, detailing its multiple benefits for reconciling energy generation with food production. Section 4 shifts to implementation realities, highlighting policy gaps, ownership models, and the strategic opportunity presented by the PM-KUSUM scheme in advancing the APV landscape. This analysis is grounded in two contrasting field-based case studies that highlight the practical challenges and possibilities of two operating models. Section 5 synthesizes these insights into concrete policy recommendations, while Section 6 concludes by positioning PM-KUSUM as a policy framework for transformation. The conclusion emphasises that while the APV offers promise, scaling it will require a coordinated policy framework to remove implementation barriers systematically.

II. BEYOND THE FALSE BINARY OF ENERGY AND AGRICULTURE

A. The Water-Energy Nexus

Since 1960, the transformation in Indian agriculture has revealed a fundamental paradox of state-led development—policies designed to democratise access to groundwater created new forms of social and environmental distortions and hierarchies. The evolution of energy-intensive irrigation systems in place of manually driven water extraction reflects not just technological progress but also a profound reconstruction of rural political economy. Private tube wells, High-Yielding Variety (HYV) seeds, fertilisers, herbicides, and mechanised inputs since the Green Revolution have sparked a rapid expansion of groundwater irrigation. Factors such as easy availability, assured supply, minimal capital investment, the shortest possible payback periods, and focused energy subsidies rendered autonomous groundwater irrigation the pillar of agricultural progress. Electricity consumption in agriculture increased exponentially from 4,470 GWh in 1971 to 2,40,800 GWh in 2023 [3]. In many states, the government actively favoured electric pumps by reducing tariffs per unit to maximise their use. Such policies reduced operational costs, increased irrigation reliability, and empowered farmers, forming them into a strong political constituency. The cost of electricity subsidy is high in Southern and Western India, where over 85% of the pumps are driven by electricity, compared to Eastern India, where the share of diesel pumps is more than 60% [4].

Farm power subsidies were designed to support small farmers, but they have disproportionately benefited large, irrigated farms, heightening rural inequalities. In situations where assets are distributed unevenly, uniform subsidies perpetuated social inequalities and pushed the power sector into a subsidy trap. Many state electricity boards are now in financial stress. According to the RBI report, the total outstanding debt of Distribution Companies (DISCOMs) rose from INR 4.2 lakh crore in 2016-17 to INR 6.8 lakh crore in 2022-23 [5]. High debt and ongoing financial losses lead to grid instability, reduce investment in infrastructure, and ultimately undermine power supply quality. With deteriorating power quality and frequent power failures, consumer defaults rise, further accentuating the losses of the State Electricity Boards (SEBs). This increases the government's subsidy burden.

Beyond economic distortions, the subsidy-driven energy-intensive agriculture model has created serious environmental challenges. Agriculture's share of India's Greenhouse Gas (GHG) emissions stands at nearly 13.4%, primarily from rice cultivation, livestock and soil management. Groundwater pumping for irrigation is a significant source of CO_2 emission because of its high energy demand [6]. A 7 HP diesel pump, irrigating one hectare of crops (groundnut, bajra, wheat, barley), consumes nearly 660 litres of diesel, releasing 1,716 kg of CO_2 into the atmosphere [7]. On the contrary, electric pumps often emit more because the electricity grid is coal-dependent. An inefficient rural electricity network makes electric pumping even more carbon-intensive, releasing more CO_2 per 1000 cubic meters lifted than diesel. This carbon-intensive irrigation reflects systemic inefficiencies embedded in subsidy structures. The availability of free power has significantly aggravated the groundwater problem in many parts of India. The annual groundwater withdrawal far exceeds natural recharge rates, leading to a decline in water tables. This raises the cost of irrigation. Groundwater crisis is acute, particularly in Punjab, Haryana, Rajasthan, Gujarat, and Tamil Nadu. The groundwater withdrawal exceeds the sustainable recharge limit by 35% in Haryana, 64% in Punjab, and 49% in Rajasthan [8].

B. The Renewable Energy Opportunity

In the era of climate change, the solution to this irrigation-energy nexus is not to overturn the advantages of groundwater irrigation but to decarbonise the energy source. In fact, the argument is that only such a transition can bring about a significant change in water and energy use systems. Policies that facilitate this energy transition have the potential to revolutionise the economy, society, and the environment. In recent years, the convergence of three trends has created an unprecedented policy opportunity for this change. Firstly, the cost of solar photovoltaic modules has fallen drastically, from INR 200/kW in 2010 to INR 9/kW in 2024 [9]. Second, India has enhanced renewable targets post-2022, from 175 GW to 500 GW by 2030, and third, efforts to decarbonise

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agriculture by reducing its GHG share have gained policy priority [10]. Taken together, these developments have made solar irrigation both economically viable and politically imperative.

Recognising this opportunity, many state governments have pioneered innovative approaches to solar irrigation across different regions: in Western India, grid-connected schemes have gained traction, such as Suryashakti Kisan Yojana (SKY), launched in 2018 in Gujarat, and Mukhyamantri Saur Krushi Vahini Yojana (MSKVY), launched in 2017 in Maharashtra. In Eastern India, the focus was on off-grid Solar Irrigation Pump (SIP) schemes. For instance, Odisha launched the Soura Jalnidhi Yojana in 2018, and Chhattisgarh launched the Saur Sujala Yojana in 2016. These various solar irrigation schemes attempted to demonstrate that solarising irrigation can be India's most cost-effective option for integrating Renewable Energy (RE) into its agriculture system. However, their limited scale on the ground reflects a deeper structural constraint on how RE schemes can scale within institutional arrangements that exist around subsidising fossil fuel (electricity) consumption.

The approaches towards climate mitigation in India throws a fundamental policy paradox. The RE strategies designed to address climate vulnerabilities in the agriculture sector are themselves displacing agricultural production. For example, MNRE approved 61 solar parks, with a total installed capacity of 40 GW in 2022 [11]. Similarly, the opposition to the proposed Indosol solar project in Nellore district, where residents and farmers contested land acquisition for large-scale solar installations, exemplifies this tension between renewable energy expansion and agricultural land rights. Large scale solar parks require extensive agricultural land areas, thereby intensifying competition between renewable energy infrastructure and agriculture production systems. Climate policies which are intended to build resilience can undermine food security, creating direct land use conflicts. Such contradiction points out that the deeper conceptual flaw: energy and food security are framed as competing objectives rather than a complementary targets.

This land competition reflects some deeper structural problems in India's development model. The agriculture sector employs 46.1% of India's workforce [12] and consumes 17.52% [13] of the nation's electricity yet only contributes 18.8% to GDP (2023-24) [14]. This imbalance seems to rationalise the need to reallocate land from "low productivity" agriculture to "high value" RE projects on agricultural land. Displacement of smallholder farmers and their farmland for large-scale energy projects is a regressive transfer, taking land from low-income rural farmers and supplying energy to urban and industrial consumers. This persistent false binary reflects institutional coordination challenges across multiple levels. For instance, renewable energy policies are developed primarily by energy ministries, with relatively limited involvement from the agriculture department. At the same time, agricultural authorities may have reservations about certain energy transitions and their implications for farming systems. In the absence of closer coordination, this separation can sometimes lead to challenges in aligning policies across sectors. India, on the one hand, heavily subsidises electricity for farming, encouraging practices that lock agriculture into energy-intensive methods. On the other hand, it invests aggressively in solar power, which often competes for the same land that farmers depend on. Such conflicting goals perpetuate rather than resolve the underlying tension between energy and agricultural objectives.

This paper argues that Agriphotovoltaics (APV) can address India's energy-agriculture paradox by overcoming the false binary. The paper critically assesses the institutional, technological, and economic barriers that limit the scale-up of RE alternatives in agriculture beyond experimental pilots. While APV offers theoretical promise as a paradigmatic shift toward farmer-centric energy production, its implementation reveals complex trade-offs that must be addressed. Our analysis suggests that, though the Pradhan Mantri Krishi Kisan Urja Suraksha Evam Utthaan Mahaabhiyan (PM-KUSUM) scheme under Component A offers a policy framework for this transformation, several implementation bottlenecks may hinder it, preventing it from genuinely supporting a farmer-centric energy transition.

C. PM-KUSUM: High Promise and Uneven Delivery

Building on state-level solar schemes, the Government of India launched the INR 34,322 crore PM-KUSUM scheme in 2019, the most significant planned transition in the agriculture sector, with a target of adding 34,800 MW of installed solar capacity by 2026.

The scheme has three ambitious components: installation of 10,000 MW of decentralised solar energy through small solar plants on barren or agricultural land (Component A); deployment of 14 lakh standalone solar pumps (Component B); and 35 lakh grid-connected solarised pumps (Component C) [15]. This represents a critical shift towards decentralised, farmer-oriented clean energy while addressing the long-standing dependence on diesel and subsidised grid electricity.

However, its implementation has remained uneven. Progress has concentrated mainly on standalone solar pumps (Component B), with 74.2% of sanctioned capacity implemented, while decentralised grid-connected solar plants (Component A) achieved only 7.2%. and solarisation of existing grid-connected pumps (Component C) has also remained slow, with only 21.3% of implementation under Individual Pump Solarisation (IPS) and 33.7% under Feeder Level Solarisation (FLS) as of December 2025. State-level performance under Component A reflects stark disparities. Rajasthan leads, with an installed capacity of 466.75 MW, driven by proactive DISCOM support, land availability, and strong participation from developers and farmers. Other states, such as Himachal Pradesh (with a small installed capacity), Madhya Pradesh, and Haryana, have achieved only modest success. Nearly half of all Indian states have zero installed capacity, despite sanctioned allocations. Such glaring disparities among states stem from complex tendering processes, poor DISCOM finances, limited farmer awareness, and land-leasing hurdles. DISCOM financial health differs significantly across states, with many unable to make timely payments to solar energy producers. Additionally, complex administrative processes involving sequential clearances from the revenue, agriculture, and energy departments result in bureaucratic inefficiencies.

Unless such obstacles are taken into consideration, Component A's potential to provide farm income stability and support the energy transition will remain unrealised.

This paper focuses on Component A of the PM-KUSUM scheme, as we believe it offers the most significant potential to transform the agriculture-energy nexus into a dual-income opportunity for farmers. Unlike standalone solar pumps, Component A enables energy sales, providing stable income streams that can diversify farm incomes and offset risks from climate-induced crop losses. This component is relevant, as the majority of Indian farmers are small and marginal farmers with less than two hectares of land, and their per capita monthly household income (including farm and non-farm) remains modest and often insufficient to meet their basic needs. Component A's integration with land-use models, such as APV, enables productive use of land for both crops and solar energy. Thus, it achieves not only energy transition by decarbonisation but also enhances rural economic resilience. We argue that neglect of these co-benefits represents a significant missed opportunity for the nation.

III. APV-A PARADIGMATIC SOLUTION

A. Understanding APV

The structural bottlenecks constraining Component A reveal a deeper challenge: scaling solar in agriculture must not compete with crop cultivation; instead, it must complement it. APV emerges as precisely this integration, allowing the same parcel of land to produce food and electricity simultaneously.

In an APV system, solar panels are elevated to 3-4 meters above the crops and fixed at an optimised angle to ensure the crops receive sufficient space and light without compromising yields, and to generate solar energy as a third crop. Rather than restricting sunlight, the panels create a favourable microclimate through partial shading. Shade-tolerant horticultural crops, such as tubers, tomatoes, and leafy greens, have shown improved productivity under these conditions. The dual-use approach is valuable in areas where expensive diesel-powered irrigation and equipment increase agricultural costs. On-site solar generation can reduce irrigation energy costs.

B. Agronomic and Environmental Benefits

Field experiments in arid and semi-arid regions, including pilot projects in Madhya Pradesh, Maharashtra, and Gujarat, indicated that APV can reduce irrigation water demand and lower temperatures. Such benefits are salient in regions where heatwaves and drought are compounded by climate change. Partial shading reduces moisture evaporation from the ground while improving the plant's resistance to harsh weather conditions by reducing thermal stress. However, these benefits cannot be generalized across diverse agro-climatic zones. What might work in Gujarat's arid conditions may not work in Kerala's monsoon agriculture. Water savings also depend on crop selection and irrigation timing. Currently, such datasets do not exist in the APV context. Therefore, to understand the APV impacts across different climates and agricultural settings, more regional studies are required. It will help identify evidence gaps and inform future policy and implementation strategies.

C. APV as a Risk Buffer

Beyond agro-ecological benefits, APV also helps address farm income volatility. For farmers, who dominate and have limited resilience to external shocks, APV can act as a risk buffer. A 1 MW APV plant, if spread over 5-6 acres, can generate approximately 4,500 units of energy if operated for 4-5 hours/day, independent of crop performance (Author's own calculation). Selling these energy units at a competitive Feed-in-Tariff (FiT) provides a guaranteed revenue stream, functioning like crop insurance during droughts or price crashes. Energy income can make the difference between coping and crisis. Farmers can reinvest these earnings in better seeds, inputs, or climate-resilient infrastructure, reinforcing agricultural stability and creating a cycle of improved farm productivity and income diversification.

IV. POLICY GAPS, OWNERSHIP MODELS AND THE PM KUSUM OPPORTUNITY IN APV LANDSCAPE

A. Current Policy Landscape and Definitional Challenges

Currently, without a coordinated framework, India's APV definition has unfolded in varied and fragmented ways across different entities. In some cases, it is approached mainly as a land-use efficiency tool, maximizing solar energy output with limited attention to agricultural returns. Others interpret it as a source of power for irrigation purposes, without emphasising its dual optimal potential. Without the precise definition and standards that place farmers at the centre, protecting crop yields, maintaining soil health, and diversifying income sources, the APV model will only prioritise energy potential while sidelining its agricultural potential.

Globally, the most successful APV strategies have demonstrated that farmer-centric definitions are essential. India must adopt frameworks that define APV as simultaneous and synergistic land use, with farmers retaining land rights while earning dual income from crop production and solar energy sales. It positions farmers not merely as energy consumers but as energy producers in India's clean energy future.

B. Three Operating Models: A Critical Assessment

Currently, three distinct models operate in India, each with different implications for farmer welfare and rural equity.

A. **The Developer-Led Model Involves Farmers** leasing their land to private entities. In return, the farmer gains rental income. While it helps farmers receive immediate financial returns, it undermines their agency by taking control of their land from them and limiting their access to potential returns from dual land use.

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B. **R&D Led Model**, which academic institutions mainly install, is helpful in learning objectives but remains constrained by its scale and is heavily reliant on grant funding. At the same time, such models aid in knowledge generation, but they lack the scalability necessary for transformation.

C. **The Farmer-Owned Model** under PM-KUSUM component A, closely aligns best with farmer-centric goals. It enables farmers to generate and sell solar power on their own land, under 25-year PPAs, without compromising land ownership. However, this model faces several barriers, including high capital costs, complex tendering, and regulatory delays.

C. PM-KUSUM as an Enabling Framework

The PM-KUSUM scheme offers enabling policy space for scaling APV deployment. Component A allows decentralised, grid-connected solar plant installations on agricultural land without displacing agrarian production. By integrating APV into this existing framework, through clear technical standards and streamlined approval processes, India can democratise clean energy generation while strengthening rural livelihoods. Such a policy approach would transform APV from a scattered set of pilots into a mainstream tool for climate resilience and rural income stability.

D. Evidence from Implementation: Comparative Case Studies

This section focuses on real-world case studies of developer-owned and farmer-centric models. It presents a comparative analysis of these models along with their respective trade-offs.

i. Case I: Transitioning from PV to APV in Rajasthan

In India, the solar energy transition faces a fundamental challenge: rising competition between solar deployment and agricultural land use. While the ambition of APV under PM-KUSUM holds immense promise, its on-ground deployment remains limited. To date, only Madhya Pradesh has successfully deployed an APV plant under the scheme, indicating a substantial gap between policy vision and its delivery.

Our paper examines the Kundanpur pilot in Rajasthan under PM-KUSUM, implemented by the Indian Council for Research on International Economic Relations (ICRIER). The project retrofits a conventional ground-mounted solar plant into an elevated APV system. It provides a comprehensive techno-economic analysis, comparing three scenarios: Traditional farming, ground-mounted PV and an integrated APV system with Viability Gap Funding (VGF)

ii. Contextualising the Challenge

Rajasthan presents a compelling case for deploying APVs. The state leads in deploying ground-mounted solar plants under component A, yet such expansion has increasingly occurred at the expense of productive agricultural land. Studies indicate that continued expansion of ground-mounted PV on agrarian land directly displaces crop production, threatens rural livelihoods, and undermines long-term food security. Rajasthan has the highest solar irradiance with (5.3 kWh/m^2 average) [16], and therefore provides an ideal environment for solar energy generation, but it must bring balance against agricultural sustainability. Without strategic intervention, the current trend may signal a permanent shift toward energy generation on farmland, potentially compromising food security in a state already facing climatic vulnerabilities.

iii. Methodology and Site Characteristics

The pilot site is in Kundanpur village, Jaipur district, which is predominantly a dryland region with hot, arid conditions and high rainfall variability. The climatic challenges necessitate integrated solutions such as APV to stabilise water and income sources for farmers.

The 2.96-acre pilot site, originally (without solar infrastructure), cultivated pearly millet(bajra) and wheat under baseline conditions, generating an income of INR 40,000 per acre per year. Currently, the farmer operates a 600kW ground-mounted solar project under Component A, with a capital cost of INR 2 crore. ICRIER is retrofitting the existing PV plant into an APV system with elevated panels, at an additional fee of about 10% of the total capex, provided as VGF. The pilot aims to explore how PM-KUSUM can leverage food and energy production on the same land in Rajasthan, exemplifying APV as a twofer solution, multiplying farm income while preserving agricultural production.

Table I: Details of Kundanpur APV Plant

Variable	Values
Project Size (MW)	0.6
Useful Life (Years)	25
Debt Ratio	70 %
Equity Ratio	30 %
Equity Amount (INR)	60,00,000
Discount Rate (%)	11.46
Electricity Tariff (INR/kWh)	3.14
Loan Tenure (Years)	15
Interest Rate (%)	10.25
Total Project Cost (Ground Mounted Plant)	2,00,00,000
Viability Gap Funding	20,00,000
Total Land (Acre)	2.96

Source: Author's Own

iv. Economic Performance Analysis: Kundanpur Pilot Results

In this economic analysis, parameters across all three scenarios remain consistent: a 0.6 MW solar plant installed over 2.96 acres, with a total ground-mounted plant cost of INR 2 crores. The financing structure comprises 70% debt from the State Bank of India (SBI), repayable over 15 years at 10.25% interest, and 30% equity. Net generation efficiency is considered to be 99.25% after accounting for losses (mismatch, thermal, or wiring). The elevated APV structure requires more than any conventional ground-mounted plant, necessitating targeted financial intervention. In this scenario, ICRIER has provided a VGF of INR 20 lakhs to bridge the cost differential between traditional and elevated systems, allowing simultaneous crop cultivation and solar energy generation. The electricity produced by the APV plant is supplied to the regional

DISCOM, Jaipur Vidyut Vitran Nigam Limited (JVVNL), at a tariff of INR 3.14/kWh.

v. Comparative Economic Analysis

Table II: Economic Feasibility Analysis of Ground-Mounted and APV Plant, Kundanpur, Rajasthan

Models	Land Use	Net Profitability (INR/Acre/ Year)	Payback Period (Years)	IRR (%)	Key Features
Traditional Farming	Agriculture Only	40,000	N/A	N/A	Baseline Crop Income
Ground-Mounted PV	Solar Only	3.86 lakh	6.9	16	No Agriculture Possible
PV with VGF	Dual Use (Solar +Agriculture)	4.54 lakh	5.3	19	Subsidised Capital Cost and Agriculture Income (1 Lakh/Acre/Year).

Source: Author's Own

The Kundanpur model presents a comparative economic analysis of three distinct land-use scenarios, demonstrating the financial viability of agrivoltaic systems relative to conventional farming and standalone solar installations.

vi. Scenario 1: Traditional Agriculture

Under the baseline scenario, without any solar technological intervention, the farmer practices conventional agriculture (including wheat and bajra) and receives the lowest annual returns of INR 40,000 per acre. These low figures reflect the constraints of traditional farming practices in semi-arid regions where climate variability and water scarcity affect productivity.

vii. Scenario 2: Ground-Mounted Solar PV

Under the Ground-mounted systems scenario, photovoltaic systems generate significantly higher returns of INR 3.86 lakhs per acre annually by selling solar energy to discoms, with a payback period of 6.9 years and an internal rate of return (IRR) of 16%. Although this scenario offers financially superior returns compared to traditional farming, it necessitates the complete cessation of agricultural activities, potentially raising concerns about food security and eliminating traditional livelihoods.

viii. Scenario 3: APV System with VGF

Under this scenario, the APV system with VGF is the most economically viable option, producing INR 4.54 lakhs per acre annually from both solar energy and agricultural production. The payback period is shortened to 5.3 years, with an improved IRR of 19%, due to VGF, which functions as a subsidised capital expense. This scenario promotes a dual-use, farmer-centric APV model that preserves agricultural functionality while incorporating solar energy generation.

ix. Financial Innovation: VGF

The VGF acts as a capital subsidy, reducing additional upfront capital infrastructure costs and improving the financial viability. The 10% additional cost for elevating structures is effectively covered through VGF, making the APV system competitive with conventional installations. The Kundanpur pilot demonstrates that, with appropriate financial instruments under the PM-KUSUM policy framework, the cost differential between conventional PV and APV systems can be addressed.

x. Case II: Contrasting Ownership Models - Developer vs Farmer Benefits

- **Developer-Led Model: Najafgarh Case**

On the one hand, the Kundanpur pilot highlights the financial potential of farmer-owned APVs with targeted support; the developer-owned model presents a different perspective. In India, a significant number of pilots are operating under developer ownership. The developers act as architects and visionaries for the APV plant, guiding the project from initial concept through to the installation's completion. One such pilot is in Najafgarh, Delhi, which showcases how the system's ownership structures affect the feasibility and profitability for developers and farmers alike.

In this plant, the developer entered into a land lease agreement with the farmer for the 4.5-acre agricultural land available. He then installed the 2.5 MW APV setup on the land and is hence selling the electricity to the grid, Bombay Suburban Electric Supply (BSES) Rajdhani, at an FiT of INR 5.1/kWh. This provides the developer with a revenue stream.

Before the project ever came into play, the pilot plot in Najafgarh was affected by groundwater salinity and supported only rabi crops such as wheat and mustard, generating roughly INR 41,000 per acre annually. This low productivity of land trapped the farmer in a persistent low-income cycle.

Under the APV land lease agreement, the farmer has secured a guaranteed annual income of INR 1 lakh per acre for 25 years: more than double his previous returns, while transferring all the agricultural and energy risks to the developer. The developer in the APV setup introduced high-value crops such as potato and turmeric, supported by freshwater irrigation, generating about INR 1.5 lakhs per acre annually. Here, the farmer benefited from stable, risk-free land-lease income, whereas the developer accrued the agricultural and energy returns.

Table III: Details of the Najafgarh Plant

Variable	Value
Project Size (MW)	2.5
Useful Life (years)	27
Land size (Acres)	4.5
Total Capital Cost (in Crores)	11,25,00,000
Debt Equity Ratio	70:30
Loan Tenure and Interest Rate	7 years and 8.5 %
Annual Net Energy Generation (kWh)	41,29, 793
Feed- in Tariff (INR/kWh)	5.10
Annual Energy Income (in Crore)	2,17,36,942

Agricultural Income (in Lakh)	675000 (Considering agricultural income of INR 1.5 lakhs/acre/year)
Payback (years)	6
Internal Rate of Return (IRR) (in %)	25

Source: Author's Own

Before APV installation, Farmer earned INR 41,000 per acre annually from conventional crops such as wheat and mustard. Post-installation, the farmer receives INR 1 lakh per acre annually as rental income, while all agricultural and solar revenue goes to the developer.

With a capital cost of INR 4.55 crore/MW, structured with a 70:30 debt-equity ratio and a 7-year loan at 8.5% interest, the plant generates 41.2 lakh kWh annually. Power sales at a FiT of INR 5.10 yield INR 2.17 crore in the first year, with an annual degradation of 0.7% per annum until the end of the 25th year of the project. The payback period is 6 years, with an IRR of 25%, underscoring the model's financial robustness.

Table IV: Comparative Analysis of Developer and Farmer-Owned Model

Model Type	Farmer's Income Potential	Developer Income Potential	Land Control	Risk Bearer
Traditional Farming	Low	Not applicable	Farmer	Farmer
Developer Led APV	Low, primarily rental-based	High (from solar crops)	Developer	Developer
Farmer Owned APV (with VGF)	High (solar +crop benefits)	Not applicable	Farmer	Farmer

Source: Author's Own

This comparison reveals stark differences between the two models. In a developer-led model, farmers benefit from rental income without bearing capital risk, but lose control over land use and forego substantial solar income. The developer receives most of the value creation from dual land use. In contrast, the farmer-owned APV model under PM-KUSUM allows farmers to enter into direct contracts with DISCOMs under power purchasing agreements, retaining the full income from solar and agriculture. This model, despite lower FiT and smaller installed capacity, can generate nearly ten times the per-acre income of the baseline agriculture, while maintaining land ownership and control.

The comparison highlights that while each model promotes dual land use and India's solar energy future, their implication on farmers' welfare and rural equity diverge significantly. The developer-led model offers large-scale deployment but converts farmers into passive landlords. In contrast, the farmer-centric model under PM-KUSUM operates at a small scale, allowing farmers to participate in the RE transition and substantially enhance their income.

The comparison highlights that each model has distinct trade-offs. The developer-led model offers relatively greater advantages in technical expertise, maintenance capabilities, and grid connectivity, which might be difficult for individual farmers to replicate. They also enable large-scale deployment, potentially achieving better market penetration. However, they transform farmers into landless farmers rather than active participants in the solar energy economy.

This ownership question reflects a broader issue in India's energy transition path: whether benefits should accrue to developers and big farmers, or be equitably shared with rural communities. PM-KUSUM experience indicates that without deliberate policy design in favour of farmer ownership, a dynamic pricing scenario will fall back on developer models with quicker deployment but with fewer rural equity benefits.

V. POLICY RECOMMENDATIONS

APV presents a viable solution to India's dual challenge of energy security and agricultural sustainability. However, the current policy landscape inadequately addresses the structural barriers that prevent farmers from accessing this transformative technology. To achieve that, APV deployment should serve the interests of India's agrarian economy rather than just developer-based energy portfolios; a comprehensive policy framework requires these four critical dimensions.

A. Standardisation and Technical Specifications

The government should draft national APV standards that are farmer-friendly, with clear criteria defining what qualifies as APV. The focus should be on protecting crop yields by mandating a maximum farm yield loss threshold of 10%. Innovations are required in panel design, spacing ratios, and crop selection criteria to balance energy and agricultural yields. Moreover, this technical specification should be regionally calibrated to capture cropping patterns, soil conditions, and climatic factors across various agro-ecological zones. Without such agriculture-centric technical standards, APV risks becoming another form of land acquisition for energy expansion, essentially replicating ground-mounted PV on agricultural land.

B. Financial Architecture

APV, being capital-intensive, inherently favours large landholders and private entities. The current status of APV plants justifies this statement. One of the biggest challenges for smallholders is the high upfront cost. To offset this, targeted capital subsidies can be introduced. Currently, financing structures are typically capped at 60-70% as debt. To address this constraint, increasing the debt share to 85% through priority-sector lending could be introduced for megawatt-scale APV installations owned by farmer institutions. Given that APV systems cost 10-15% more than conventional solar installations, introducing FiT premiums for farmer-owned models becomes essential to incentivise and strengthen Farmer Producer Organisation (FPO) involvement. Additionally, targeted capital subsidies can help offset the higher cost of panel elevation and make the APV system crop-friendly.

C. Institutional Innovation and Coordination

Individual APV installations on small plots are economically unviable due to high per-unit cost. FPOs can emerge as a critical institution for bringing farmers together and achieving the scale necessary for viable APV installations. They can facilitate the collective ownership models while ensuring that benefits accrue directly to farming communities. To transition APV from pilot projects to scalable, farmer-centric commercial models, a coherent policy ecosystem is imperative. MNRE should establish an APV monitoring and grievance redressal cell with representatives from the agriculture, revenue, and energy departments to streamline approvals, facilitate holistic APV development and implementation, and resolve conflicts. To enhance stakeholder confidence, a single-window clearance system should track commissioning, payment timelines, and bottlenecks.

D. Research and Development Strengthening

Scaling APV requires agronomic and technological innovations suited to various agro-climatic conditions. The 110 kWp APV plant at ICAR Delhi demonstrates the essential role of premier agriculture research institutes in advancing this innovation. The government should expand such decentralised R&D across agricultural universities and ICAR centres.

VI. CONCLUSION

APV emerges as a critical innovation that bridges climate action and rural development as India moves towards its 2070 net-zero targets. The paper demonstrates that farmer-centric models can contribute to RE targets and enhance food security while generating 9-10 times higher income than traditional farming. However, achieving this potential requires a fundamental shift from current policy approaches. Rather than creating energy and agriculture as competing sectors, India must embrace integrated frameworks that position farmers as active participants in the energy transitions.

Although the PM-KUSUM policy offers an institutional foundation for this transformation, removing implementation barriers through coordinated policy interventions will be necessary for it to be effective. Transformation from the current developer-dominated APV systems to an inclusive, farmer-centric APV model requires coordinated policy interventions across technical, financial, institutional, and regulatory domains. The proposed four-pillar framework represents not merely a sectoral reform but a fundamental reimagining of how RE development can serve agricultural interests rather than supplant them. Successfully implementing these measures will determine whether APV can truly augment farmers' income and align with the energy transition in rural livelihoods.

DECLARATION STATEMENT

We hereby declare that the manuscript is an original, unpublished work and has not been submitted to any other journal for consideration. The research presented in this manuscript is based on genuine data and analysis undertaken by the authors. All ethical standards and guidelines specified by the journal have been duly followed. We also confirm that:

1. All authors have contributed significantly to the work.
2. All authors have read and approved the submitted version of the manuscript.
3. There is no conflict of interest related to this submission.
4. Proper citations and acknowledgements have been provided wherever necessary.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process. During the preparation of this work, the author(s) used ChatGPT (OpenAI) to assist with language refinement and grammar editing. After using this tool, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the published article.

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