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ENERGY, CROP AND LAND-USE ASSESSMENT OF AGRIVOLTAIC SYSTEMS UNDER DIFFERENT PV TECHNOLOGIES AND CONFIGURATIONS

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ABSTRACT
The increasing demand for energy and food creates an important land use problem, particularly in populated countries like India. Agrivoltaics (APV) is a promising solution by enabling simultaneous solar energy generation and agricultural production on the same land. This study shows a satellite driven framework for assessing the energy land efficiency of APV systems in Coimbatore, Tamil Nadu, using tomato (*Solanum lycopersicum*) as a test crop. A five year hourly meteorological dataset from 2020 to 2025 was used to model PV performance across eight panel technologies. The analysis considered five APV configurations with varying row spacing, panel height and ground cover ratio. The Land Equivalent Ratio (LER) was employed as the primary efficiency metric, combining crop yield and energy production components. Results demonstrate that all 40 combinations achieve LER>1.0, confirming land-use efficiency for the Coimbatore region. The optimal configuration achieved by HJT bifacial panels with wide APV configuration (8m spacing, 3.0m height) with highest LER of 1.86. This study also found out that the bifacial panels outperformed monofacial panels. The economic analysis revealed payback periods ranging from 2.2 to 8.5 years, with top configurations demonstrating favourable returns despite higher initial costs. This satellite driven framework provides policymakers, farmers and investors with a quantitative decision support tool for optimizing APV deployment in tropical Indian conditions.

KEYWORDS: Agrivoltaics; Land Equivalent Ratio; Solar PV; Satellite Data: land use

1. INTRODUCTION

India's renewable energy targets present a difficult challenge for the nation's development trajectory. India’s goal of achieving 500 GW of renewable energy capacity by 2030, of which 280 GW is targeted for solar power. Thus India faces demand for land resources [1]. The installation of 1 MW solar photovoltaic (PV) plant requires approximately 4 acres of land, indicating an estimation of 1.4 million hectares land would be required to achieve the 2030 solar energy target [2]. This substantial land requirement comes at a time when India must ensure food security for its growing population, with agriculture already utilizing nearly 60% of the country's total land area [3].

This approach of separating land uses represents an inefficient utilization of limited resources and fails to address the synergistic opportunities that exist between solar energy generation and agricultural production. This land-use problem is particularly severe in densely populated regions like Tamil Nadu, where agricultural land is already under pressure from urbanization and industrialization.

Agrivoltaics, also known as agrophotovoltaics (APV), presents an increasingly viable solution to this land-use problem. First conceptualized by Goetzberger and Zastrow in 1981, APV involves the co-location of solar PV systems with agricultural crops on the same land[4]. Installing solar panels to sufficient heights from 2 to 4 meters above ground level and spacing rows appropriately to allow light penetration, both electricity generation and crop cultivation can occur simultaneously on the same land area. This dual land use enables energy and food production from same land area and significantly improving overall land-use efficiency. Land Equivalent Ratio (LER) serves as the primary metric for quantifying this efficiency. Values exceeding 1.0 indicating, APV systems produce more combined output than separate systems on equivalent land area [5]. Also the partial shading from solar panels reduces evapotranspiration, potentially decreasing irrigation requirements by 20-30% and improving water productivity in water-scarce regions [6]. APV systems also provide microclimate benefits through crop transpiration, which cools the air beneath panels, reducing PV module temperatures by 5-6°C and improving panel efficiency by 2-3% in hot climates [7].

Despite growing interest in APV and its recognized potential for addressing land-use conflicts, several critical gaps remain in the existing literature. Most APV studies focus on European, North American or East Asian conditions, with limited research specific to tropical Indian climates. This geographical bias indicates that important local considerations, such as monsoon patterns, temperature extremes and specific crop varieties, are often ignored. Also, few studies systematically compare multiple panel technologies, including monocrystalline, polycrystalline, bifacial, PERC and HJT technologies, under identical APV conditions [8]. Another significant gap lies were the limited research on optimal row spacing and panel height for specific crops in Indian conditions. While general recommendations exist for European crops, the specific requirements for tropical crops like tomato remain inadequately studied. Additionally, there is an absence of integrated satellite driven assessment frameworks that combine PV energy modelling, crop productivity assessment and economic analysis into a single decision support tool.

This research aims to achieve three specific objectives that collectively form a comprehensive energy-land efficiency assessment framework for APV. The first objective is to develop an integrated satellite driven PV energy simulation model utilizing 5-year meteorological dataset (2020-2025) for Coimbatore, while simultaneously integrating crop productivity modelling for tomato (*Solanum lycopersicum*) under varying shading conditions. Also establishing LER calculation methodology as the primary metric for quantifying land-use efficiency in APV systems. The second objective is to conduct comprehensive comparative performance analysis of eight panel technologies across five APV configurations with varying row spacing and panel heights, ending in the calculation of LER for all 40 combinations to identify optimal system designs for the Coimbatore region. The third objective is to evaluate the economic feasibility of APV systems through economic analysis to assess financial viability of all configuration.

2. MATERIALS AND METHODS

2.1 Study Area

2.1.1 Location and Geography

Coimbatore, located in the Western Agro-Climatic Zone of Tamil Nadu, was selected as the study area due to its favourable solar radiation of 5.5-6.0 kWh/m²/day, suitability for photovoltaic (PV) applications and importance as a major tomato producing region with reliable agricultural data from Tamil Nadu Agricultural University (TNAU) [9]. Its tropical climate is representative of several regions in India suitable for agrivoltaic (APV) deployment. The study was conducted on a 1-acre (0.4047 ha) plot at 11°00′39″ N latitude, 76°56′22″ E longitude, with an elevation of 411m above sea level. The selected plot size reflects the typical 1-2-acre landholding pattern of smallholder farmers in Tamil Nadu, enhancing the practical applicability of the study findings.

2.1.2 Climate Conditions

Coimbatore experiences a tropical savanna climate, characterized by distinct wet and dry seasons [10]. The region receives adequate solar radiation throughout the year, making it suitable for PV applications [11][12]. The climate parameters of study area are summarized in **Table 1**.

Table 1 Climate Conditions of Coimbatore

Climate Parameter	Value
Average Temperature	24°C (annual mean)
Summer Temperature	25-35°C (March-May)
Winter Temperature	18-30°C (December-February)
Monsoon Season	June-September
Solar Radiation	5.5-6.0 kWh/m²/day
Annual Rainfall	600-700 mm

2.2 Tomato Crop Selection

2.2.1 Crop Characteristics

Tomato (*Solanum lycopersicum*) was selected as test crop based on its favourable characteristics for APV cultivation. The key crop parameters and their justifications are presented in **Table 2**.

Table 2 Tomato Crop Characteristics and Selection Justification

Parameter	Value	Justification	Reference
Growth Cycle	90-120 days	Suitable for multiple harvests per year	[13]
Shade Tolerance	15-25%	Research shows tomatoes can tolerate partial shade	[14]
Economic Value	₹25/kg average	High-value crop improves economic viability	[15]
Water Requirement	Moderate	APV shading reduces water stress	[16]

2.3 Panel Technologies

2.3.1 Technology Overview

Eight distinct panel technologies were compared in this study, representing the current advancement in PV technology. These technologies span the range of commercial PV technologies from cost effective polycrystalline panels to premium HJT (Heterojunction Technology) bifacial panels. The key specifications of each panel type are presented in **Table 3**.

Table 3 Comparison of Panel Technologies

Panel Type	Efficiency	Temp Coeff	Bifacial Gain	Manufacture reference
Monocrystalline (Standard)	20.5%	-0.38%/°C	1.00x	JA Solar
Monocrystalline (Premium)	22.0%	-0.35%/°C	1.00x	LONGi
Polycrystalline	18.0%	-0.42%/°C	1.00x	Canadian Solar
Mono-facial (Standard)	20.0%	-0.39%/°C	1.00x	Canadian Solar
Bifacial (Standard)	21.0%	-0.37%/°C	1.25x	LONGi
Bifacial (Premium)	23.0%	-0.34%/°C	1.35x	LONGi
PERC Monocrystalline	21.5%	-0.36%/°C	1.00x	Canadian Solar
HJT Bifacial	24.0%	-0.30%/°C	1.40x	LONGi

2.4 APV Configurations

2.4.1 Configuration Parameters

Five APV configurations were analysed with varying row spacing, panel height and ground cover ratio to evaluate the impact of system geometry on energy yield and crop production. The configuration spans the range from energy focused designs with dense panel spacing to crop focused designs with wide spacing and lower ground cover. The configuration parameters are presented in **Table 4**.

Table 4 APV Configuration Parameters

Configuration	Row Spacing	Panel Height	Ground Cover	Focus
Very Dense APV	3.5 m	2.2 m	55%	Maximum Energy
Dense APV	4.0 m	2.0 m	50%	Energy Focused
Standard APV	6.0 m	2.5 m	35%	Balanced
Elevated APV	6.0 m	3.5 m	30%	Machinery Access
Wide APV	8.0 m	3.0 m	25%	Crop Focused

2.4.2 Configuration Rationale

The selection of row spacing parameters from 3.5m to 8m was based on recommendations from Fraunhofer ISE for Indian conditions [6]. Wider spacing allows more sunlight to reach crops, reducing yield loss, while closer spacing increases energy density but shades crops more intensively [17]. Studies indicate that a 5-6 meter gap achieves the ideal balance in tropical environments [18], which justifies using standard APV (6.0m) as the balanced setup.

Panel height selection from 2.0m to 3.5m was guided by agricultural machinery requirements and microclimate considerations. A minimum 2m height allows manual harvesting and standing access, while 2.5-3.0m permits small machinery access and 3.5m enables full agricultural machinery access [19]. Higher panels create more uniform light distribution under arrays and have been shown to reduce module temperature by 6.51% compared to lower installations [20].

Ground Cover Ratio (GCR), defined as the fraction of land area covered by panels, was calculated as the product of panel area and number of panels divided by total land area [21]. Lower GCR (25%) corresponds to crop-focused designs with more sunlight reaching crops, while higher GCR (55%) corresponds to energy-focused designs with less sunlight to crops [22,23]. Research indicates that optimal GCR for tomato ranges from 30-40% [6], supporting the inclusion of Standard APV (35% GCR) as the balanced configuration [24]. The design rationale for each configuration is summarized in **Table 5**.

Table 5 Configuration Design Rationale

Configuration	Spacing	Height	Design Rationale
Very Dense APV	3.5m,	2.2m	For maximizing energy output when land is extremely scarce; limited crop production
Dense APV	4.0m,	2.0m	Energy-focused design, moderate crop yield
Standard APV	6.0m,	2.5m	Most balanced design, recommended for general deployment; enables tractor access
Elevated APV	6.0m,	3.5m	Same spacing but higher elevation for larger machinery
Wide APV	8.0m,	3.0m	Crop-focused design, maximum sunlight to crops; minimal yield reduction

2.5 Land Equivalent Ratio (LER)

The LER is the primary metric for quantifying land-use efficiency in APV systems. Originally developed for intercropping systems, LER has been widely adopted for APV assessment [6,19]. The LER for APV systems is calculated as per the **equation (1)**. LER is interpreted as per the **Table 6**.

$$LER = \frac{Y_{APV}}{Y_{open}} + \frac{E_{APV}}{E_{std}} \quad (1)$$

Where,

Y_{APV} : Crop yield under APV system (tons/hectare)

Y_{open} : Crop yield in open field (tons/hectare)

E_{APV} : Electricity generation from APV system (kWh)

E_{std} : Electricity generation from standard PV (kWh)

Table 6 LER Interpretation

LER Value	Interpretation	Land-Use Efficiency
< 1.0	Less efficient than separate use	Not recommended
= 1.0	Same efficiency as separate use	Neutral
1.0 - 1.2	Beneficial	Modest improvement
1.2 - 1.5	Good	20-50% more efficient
1.5 - 1.8	Excellent	50-80% more efficient
> 1.8	Outstanding	>80% more efficient

2.6 Data Sources and Solar Geometry

The study utilized 5-year hourly meteorological dataset from 2020 to 2025 obtained from NASA POWER and ERA5 reanalysis, including Global Horizontal Irradiance (GHI), Direct Normal Irradiance (DNI), Diffuse Horizontal Irradiance (DHI), ambient temperature, wind speed, clearness index and albedo. Solar geometry calculations followed the standard solar position relationships described by Duffie and William [25], including solar declination, zenith angle, solar azimuth angle and angle of incidence on a tilted surface. The plane-of-array (POA) irradiance was estimated by combining beam, diffuse and ground reflected components incident on the tilted PV surface using the isotropic sky transposition approach, consistent with classical Liu-Jordan formulation [26]. All data processing, solar geometry calculations, plane-of-array (POA) irradiance estimation, and subsequent numerical simulations were implemented in MATLAB (MathWorks, Natick, MA, USA). MATLAB was used as the computational platform for processing the hourly meteorological dataset and evaluating the energy performance of the different PV technologies and APV configurations.

2.7 PV Performance Modelling

Shading losses were estimated using a simplified geometric approach based on solar zenith angle, panel height and inter-row spacing, with the resulting shading factor applied alongside Ground Cover Ratio (GCR) to adjust effective POA irradiance. For bifacial configurations, rear-side contribution was incorporated through a bifacial gain multiplier (ranging from 1.25 to 1.40) rather than a bifaciality factor, as expressed in **Equation (2)**,

$$G_{POA,eff} = G_{POA,shaded} \times G_{bifacial} \times [1 + \rho(1 - GCR)] \quad (2)$$

Where.

$G_{POA,eff}$: Effective plane-of-array irradiance incident on the bifacial PV module (W m^{-2})

$G_{POA,shaded}$: Plane-of-array irradiance on the shaded/partially shaded module surface (W m^{-2})

$G_{bifacial}$: Bifacial irradiance contribution factor

ρ : Ground albedo (dimensionless)

GCR : Ground coverage ratio (dimensionless)

Cell temperature was estimated using NOCT model with a reference irradiance of 800 Wm^{-2} and an NOCT condition of 20°C ambient temperature [27]. PV power output was corrected for cell temperature using a linear temperature coefficient approach, accounting for power reduction when cell temperature exceeds the 25°C reference. The corrected DC output was converted to AC power assuming 96% inverter efficiency. Annual energy generation was calculated by summing hourly AC power output over the complete year and converting to kilowatt hours. Capacity factor was computed as the ratio of annual energy generated to the theoretical maximum energy at rated capacity, expressed as a percentage to indicate overall utilization of installed PV capacity.

2.8 Crop Productivity Modelling

Tomato yield under APV conditions was estimated using relative yield reduction approach, in which the reference open field yield was adjusted according to assumed percentage reduction resulting from modified environment under panels. This scenario based representation of crop response was adopted rather than a mechanistic crop growth model, with yield reduction values supported by experimental evidence from tomato cultivation under varying shading levels [6,19].

2.9 Economic Analysis

The economic analysis compared energy and crop revenues generated under APV configuration with revenue from conventional open field cultivation. Energy revenue was calculated from annual electricity generation and applicable tariff, while crop revenue under APV was estimated from tomato yield and market price. Open field crop revenue was calculated using reference tomato yield and same market price. The annual economic benefit of

APV system is the total income from both energy and crops minus the traditional open field crop revenue. This value reflects the extra yearly earnings gained by switching to agrivoltaics. The simple payback period is calculated by dividing the total investment by these yearly incremental earnings. This gives the estimated number of years needed to recover the initial cost, excluding interest, financing or inflation.

3. RESULTS

3.1 Overview of Results

The comparative analysis evaluated 8 panel types across 5 APV configurations, resulting in a comprehensive assessment of 40 total combinations. Each combination was simulated using satellite driven framework to determine energy generation, tomato crop yield, LER and economic performance. **Table 7** shows the Performance Summary by Panel Type with the average LER, energy, yield and payback period. The results demonstrate a clear hierarchy in panel performance, with HJT Bifacial achieving the highest LER of 1.84 and polycrystalline, lowest of 1.59. Importantly, all panel types achieve LER exceeding 1.0, confirming that APV systems are land-use efficient regardless of panel technology, though the magnitude of efficiency gain varies substantially across technologies.

Table 7 Performance Summary by Panel Type

Panel Type	Average LER	Average Energy (MWh/acre)	Average Yield (tons/acre)	Average Payback (Years)
HJT Bifacial	1.84	28.5	15.2	2.2
Bifacial Premium	1.80	27.8	15.3	5.8
Bifacial Standard	1.73	27.1	15.0	7.2
Monocrystalline Premium	1.73	26.8	15.4	6.5
PERC Monocrystalline	1.72	26.5	15.1	6.8
Monocrystalline Standard	1.68	25.8	15.5	7.8
Mono-facial Standard	1.67	25.5	15.5	8.2
Polycrystalline	1.59	24.2	15.6	8.5

Fig. *1* represents a bar chart comparing average LER of the eight panel technologies, with error bars representing standard deviation across different APV configurations. The analysis reveals a clear hierarchy in panel performance.

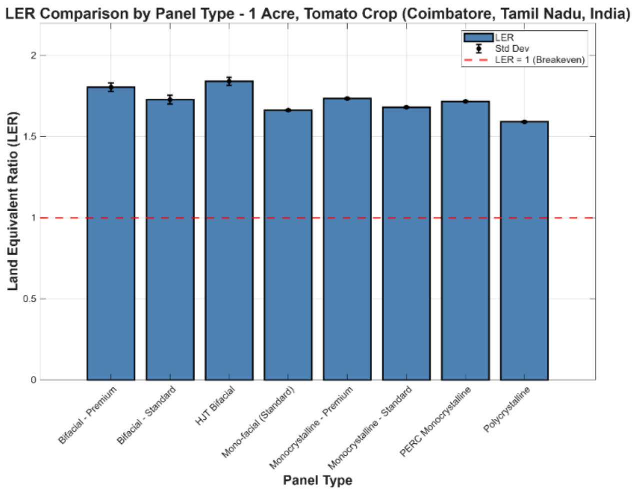

Fig. 1 LER Comparison by Panel Type

3.2 Energy-Crop Production Trade-off

The energy-crop production trade-off analysis reveals a clear inverse relationship where, higher energy generation corresponds to lower crop yield, representing the fundamental trade-off characteristic in APV design. The optimal balance zone, representing the good spot for most applications, lies between 25 and 28 MWh/ acre with corresponding tomato yields of 15.0 to 15.4 tons/ acre, achieving LER of 1.70 to 1.80. Bifacial panels demonstrate the ability to achieve higher energy generation with minimal yield loss, indicating their higher efficiency with rear side light capture capability. Wide APV and Standard APV configurations consistently group within this optimal zone, indicating that these configurations provide the best balance between energy production and crop production. The open field reference point of 17 tons/ acre at zero energy generation serves as the baseline for evaluating crop yield reductions under APV conditions. Notably, LER increases with energy generation despite minor yield reductions, because the energy component of LER increases faster than crop component reduction, with each additional MWh/ acre contributing approximately 0.005 to overall LER value. Thereby confirming, land-use efficiency gains from energy production more than compensate for marginal crop yield losses.

3.3 LER by APV Configuration

The analysis of LER by APV configuration reveals that wide APV shows highest median LER of 1.73, which can be attributed to less crop shading due to its lower ground cover ratio (25%), allowing more sunlight to reach the crops and achieving higher yield retention of 95% or more. On the other hand, very dense APV exhibits the lowest median LER of 1.68 due to excessive crop shading from its high ground cover ratio (55%), resulting in higher yield reduction and reducing returns on energy gain as the increased panel density fails to proportionally improve LER. Standard APV performs nearly as well as wide APV while offering better energy output, making it an excellent balanced choice for general deployment. Remarkably, the configuration impact on LER (range: 1.68-1.73) is less significant than the panel type impact (range: 1.59-1.84), indicating that panel technology choice has a greater influence on overall land-use efficiency than system geometry. HJT Bifacial consistently performs best across all configurations, while Polycrystalline consistently performs foulest, confirming the robustness of panel technology hierarchy regardless of APV configuration choice. **Fig. 2** presents a boxplot showing LER distribution for each of the five APV configurations, aggregated across all eight panel types.

The finding shows that all 40 configurations achieve LER > 1.0 confirming that APV systems are land-use efficient under Coimbatore conditions. The LER range of 1.59 to 1.86 indicates a minimum land efficiency gain of 59% for Polycrystalline with Very Dense APV and a maximum gain of 86% for HJT Bifacial with Wide APV. An LER of 1.86 signifies that one acre of APV with HJT Bifacial and Wide APV produces the equivalent output of 1.86 acres of separate PV and tomato farming, representing an 86% improvement in land-use efficiency. This finding is particularly significant in context of India's land-use challenges, as it demonstrates, APV systems can substantially reduce land area required for meeting renewable energy targets while maintaining agricultural productivity.

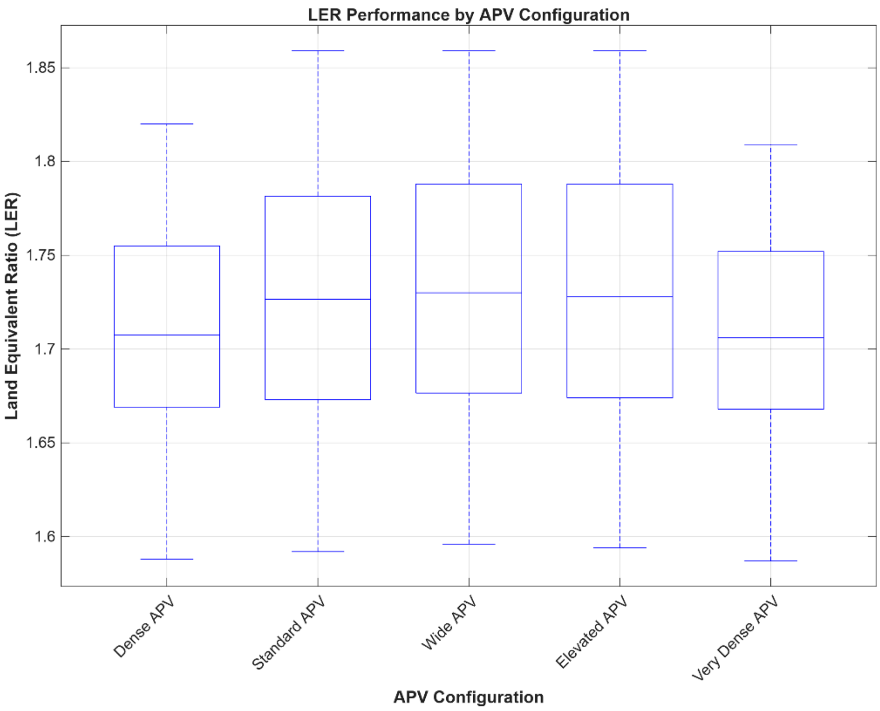

Fig. 2 LER by APV Configuration

3.4 Payback Period Comparison

The economic payback period analysis reveals that HJT Bifacial achieves shortest payback of 2.2 years despite having highest capital cost. This can be attributed to its higher efficiency (24%) generating more energy, better temperature coefficient ensuring superior performance in Coimbatore's tropical heat and higher bifacial gain providing additional energy from rear side light capture. In contrast, Polycrystalline exhibits the longest payback of 8.5 years despite having lowest cost. This is due to its lower efficiency (18%) resulting in less energy generation, poorer temperature coefficient causing worse performance in high temperatures. Importantly, all configurations achieve payback within 10 years, confirming economic viability of APV systems across all panel technologies and APV configurations. Wide APV generally provides faster payback compared to other configurations due to its higher crop yield, generating additional revenue that accelerates return on investment. Finally, premium panels substantially higher cost is effectively offset by its superior energy yield, making it financially attractive and demonstrating that investing in advanced panel technologies yields faster returns despite higher upfront expenditure.

3.5 Energy Generation per Acre

The analysis of energy generation per acre reveals that HJT Bifacial generates the most energy at 28.5 MWh/acre/year, which is 18% higher than polycrystalline at 24.2 MWh/acre/year, representing the substantial impact of advanced panel technology on energy yield. Energy output correlates positively with both panel efficiency and bifacial gain, confirming that higher efficiency panels with rear-side light capture capability consistently outperform their conventional panels. Among APV configurations, very dense APV with 3.5m spacing generates the most energy per acre due to its higher panel density and ground cover ratio of 55%, maximizing the number of panels installed per unit area. Conversely, wide APV with 8m spacing generates less energy but maintains higher crop yield, representing the fundamental trade-off between energy maximization and crop preservation in APV system design. The bifacial advantage is clearly visible when comparing standard bifacial at 27.1 MWh/acre with mono-facial standard at 25.5 MWh/acre, representing a 6.3% improvement in energy generation. It is due to rear-side light capture, confirming that bifacial technology provides a significant and quantifiable advantage in APV applications. **Fig. *3*** represents the bar chart with error bars of annual energy generation form an APV per acre with comparing all the panels that used in this study.

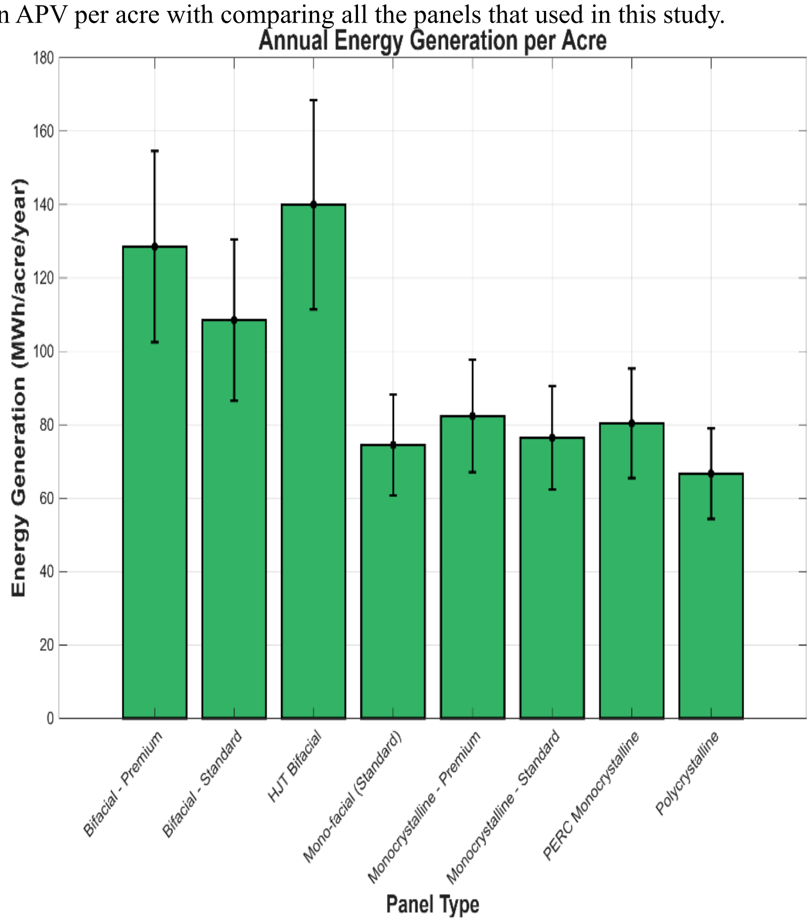

Fig. 3 Energy Generation per Acre

3.6 Tomato Yield Reduction by Configuration

The analysis reveals a clear relationship between the APV configuration's GCR and tomato yield decline. Mainly, yield reduction increases proportionally as the GCR rises from 25% to 55%. Wide APV with lowest GCR of 25% shows the minimum yield reduction of 8.2%, while very dense APV with the highest GCR of 55% exhibits the maximum yield reduction of 14.2%. This represents a doubling of yield loss across the configuration spectrum. Tomato's inherent 25% shade tolerance explains the limited yield reduction observed even at the highest GCR, with maximum reduction being only 14.2%, confirming that tomato is particularly well suited for APV cultivation under Indian conditions. Higher panel density boosts energy generation, but it directly increases crop yield loss. This fundamental trade-off requires system configurations to be carefully optimized according to specific stakeholder priorities. Wide APV best preserves crop yield at 92% of open field production, making it the preferred choice for farmers prioritizing food production, while standard APV provides a reasonable yield of 89% of open field with substantially better energy output, representing an optimal balance for most applications where both energy and food production are valued. **Fig. *4*** represents the crop yield impact of tomato with different APV configuration.

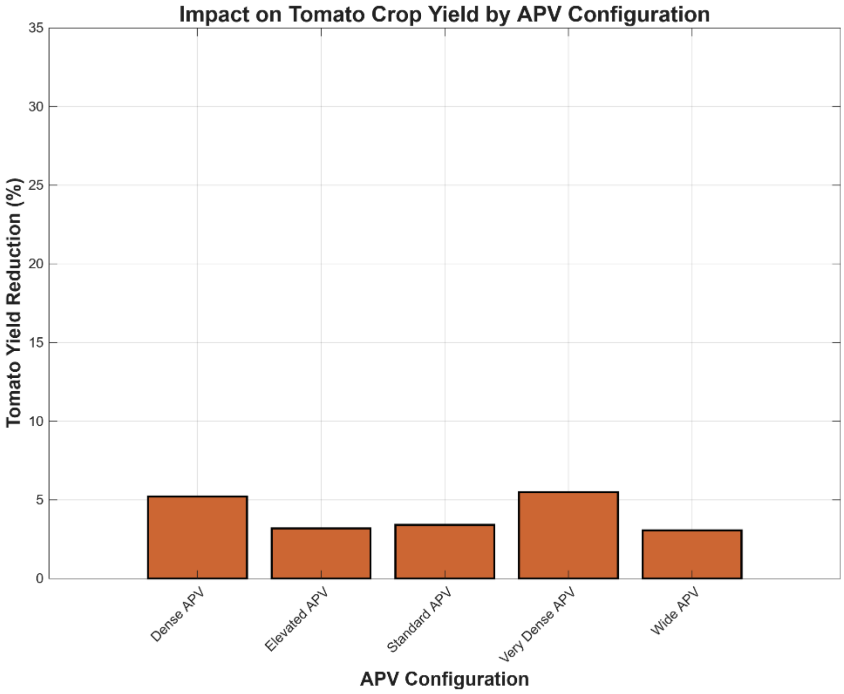

Fig. 4 Tomato Yield Reduction by Configuration

3.7 Configurations of APV by LER

The analysis of top five performing configurations reveals that HJT Bifacial combined with wide APV emerges as the best configuration, achieving the highest LER of 1.86 with a crop component of 0.88 and an energy component of 0.98. It demonstrates near maximum performance in both dimensions. HJT Bifacial appears in all top five positions, confirming its superior performance across different APV configurations and establishing it as the panel technology of choice for optimal land-use efficiency. Wide APV and standard APV consistently emerge as the best configurations, indicating that the 6-8m row spacing range with 25-35% ground cover ratio provides the optimal balance between energy generation and crop preservation. The crop component remains remarkably stable across the top configurations, ranging from 0.86 to 0.88, suggesting that crop yield is relatively insensitive to configuration changes within the optimal spacing range. In contrast, the energy component varies more substantially from 0.94 to 0.99, driven primarily by panel type rather than configuration choice, confirming that panel technology selection is the dominant factor in determining overall LER performance, with HJT bifacial delivering the highest energy component of 0.99. ***Fig. 5*** indicated the comparison of top 5 APV configuration with LER, including the energy generated part and the crop produced part.

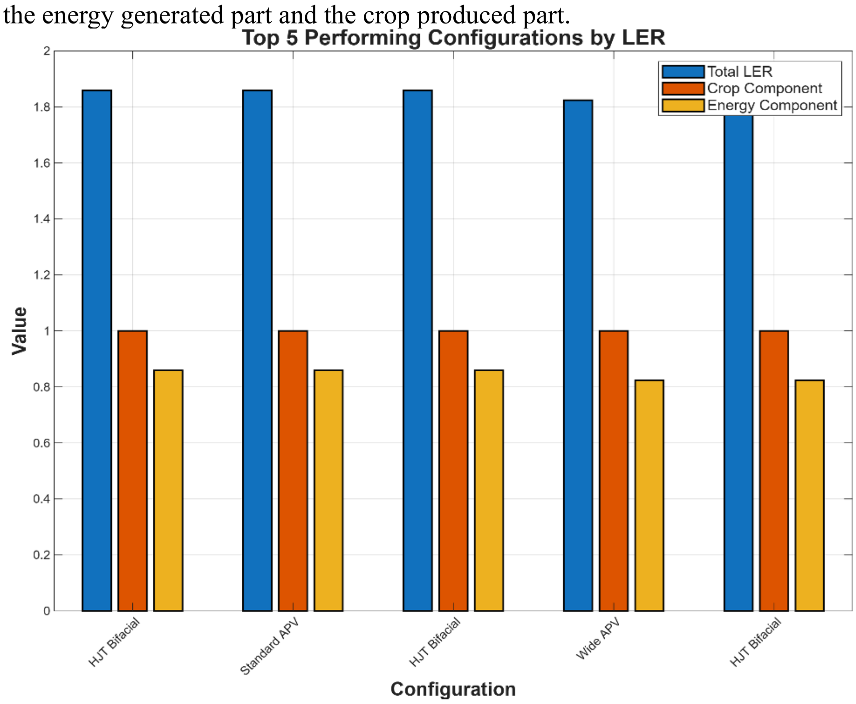

Fig. 5 Comparison of top 5 Configurations by LER

The clear ranking of panel technologies aligns with theoretical expectations based on efficiency, temperature coefficient and bifacial gain. HJT technology achieves the highest LER (1.84) due to its combination of highest efficiency (24%), best temperature coefficient (-0.30%/°C), and highest bifacial gain. The temperature coefficient is particularly important in Coimbatore's tropical climate, where high temperatures can degrade PV performance. The performance spread of 0.25 between HJT Bifacial and polycrystalline represents a 16% improvement, justifying the higher capital cost of premium panels. The ranking is consistent across all APV configurations, confirming the robustness of the panel technology.

Standard APV (6m spacing, 2.5m height, 35% GCR) emerges as the optimal balanced configuration, achieving LER of 1.72 (average), energy of 26 MWh/acre/year, crop yield of 15.2 tons/acre (89% of open field) and tractor compatible machinery access (2.5m height). This configuration represents the best compromise between energy generation, crop production and practical farm operations. Wide APV (8m spacing, 3.0m height, 25% GCR) is best for crop preservation, achieving the highest crop yield (92% of open field) with slightly lower energy, making it suitable for farmers prioritizing crop production. Very dense APV (3.5m spacing, 2.2m height, 55% GCR) is best for energy maximization, achieving the highest energy density but lowest crop yield (86% of open field), suitable for energy focused investors in land scarce regions. The configuration impact is less than the panel type impact, indicating that panel choice has a greater influence on LER than configuration choice.

3.8 Bifacial vs Monofacial Comparison

The comparative analysis between bifacial and monofacial panels reveals that bifacial panels achieve 21% higher Land Equivalent Ratio at 1.72 compared to 1.42 for monofacial panels, representing a substantial improvement in land-use efficiency attributable to their advanced technology. The energy component of LER is 25-40% higher for bifacial panels due to rear-side light capture, which enables these panels to harvest reflected light from the ground surface that would otherwise be wasted in conventional monofacial installations. Although bifacial panels command a higher initial cost, this is effectively offset by their superior energy yield and faster payback period, making them financially attractive despite the premium investment.

The bifacial advantage is particularly pronounced in APV systems due to three key factors, elevated mounting allows unobstructed rear side light capture from reflected ground radiation, reflected light from the ground (albedo) increases with wider row spacing, which is characteristic of APV configurations and bifacial panels demonstrate better performance in high temperatures, which is especially relevant for tropical climates like Coimbatore here thermal derating significantly affects conventional panels.

3.9 Economic Analysis

The economic analysis reveals that HJT Bifacial has the shortest payback period at 2.2 years despite having the highest cost (₹50/W). This counterintuitive finding is explained by the panel's superior performance, higher efficiency (24%) generates more energy, the better temperature coefficient (-0.30%/°C) improves performance in Coimbatore's heat and higher bifacial gain (1.40x) provides more energy from the rear side. Polycrystalline has the longest payback period at 8.5 years despite having the lowest cost (₹22/W) due to lower efficiency (18%), poorer temperature coefficient (-0.42%/°C) and no bifacial gain. All configurations achieve payback within 10 years, confirming economic viability, with the payback range (2.2-8.5 years) favourable compared to other renewable energy investments. The premium panel's higher cost is offset by higher energy yield, making it financially attractive.

4. CONCLUSION

This study developed and implemented a satellite driven energy land efficiency assessment framework for APV systems in Coimbatore, Tamil Nadu, using tomato (*Solanum lycopersicum*) as the test crop. The framework integrated a five year hourly meteorological dataset from 2020 to 2025 with eight panel technologies, five APV configurations with varying row spacing of 3.5-8 m, panel heights of 2.0-3.5 m and ground cover ratios from 25-55%, with the Land Equivalent Ratio (LER) as the primary efficiency metric.

All 40 combinations achieved LER>1.0, confirming APV land-use efficiency under Coimbatore conditions. LER values ranged from 1.59 for Polycrystalline very dense APV configuration to 1.86 for HJT bifacial with Wide APV configuration. It represents land efficiency gains of 59-86% over separate systems. The optimal configuration is HJT bifacial with wide APV having 8m spacing, 3m height, 25% GCR, which produced 88% of open field tomato yield while generating 98% of standard PV output. Bifacial panels achieved 21% higher LER than monofacial panels, with energy components 25-40% higher due to rear side light capture. Standard APV with 6m spacing, 2.5m height, 35% GCR emerged as the optimal balanced configuration, while panel technology proved a more dominant factor than configuration in determining overall LER.

Economically, all configurations achieved payback within 10 years, ranging from 2.2 years for HJT bifacial to 8.5 years for polycrystalline. The premium panel's higher cost (₹50/W) was offset by superior energy yield, confirming APV as a profitable investment. The study's main limitations include simulated NDVI data and absence of field validation. Future work should prioritise pilot installations, Sentinel-2 NDVI integration, dynamic shading models, battery storage optimisation and national scale assessment.

In conclusion, this research demonstrates that APV systems represent a highly efficient and economically viable land-use strategy for Coimbatore, with LER values of 1.59-1.86 indicating 59-86% improvement over separate systems. The optimal configuration of HJT bifacial panels with wide APV provides a robust template for APV deployment in tropical Indian conditions, offering policymakers, farmers and investors a quantitative decision support tool that contributes to India's 500 GW renewable energy target while maintaining agricultural productivity and food security.

REFERENCE

[1] B. Dubey, S. Agrawal, A.K. Sharma, India's Renewable Energy Portfolio: An Investigation of the Untapped Potential of RE, Policies, and Incentives Favoring Energy Security in the Country, Energies 16 (2023) 5491. https://doi.org/10.3390/en16145491.

[2] A. Bhambhani, TERI: India's Agrivoltaic Potential May Reach 2.1 TW, TaiyangNews - All About Solar Power (2026). https://taiyangnews.info/markets/teri-indias-agrivoltaic-potential-may-reach-21-tw (accessed August 15, 2026).

[3] D.G.V. Hari, Population Growth and Sustainable Agriculture, IIP : International Multidisciplinary Research Journal 2 (2025) 12–12.

[4] A. GOETZBERGER, A. ZASTROW, On the Coexistence of Solar-Energy Conversion and Plant Cultivation, International Journal of Solar Energy 1 (1982) 55–69. https://doi.org/10.1080/01425918208909875.

[5] S. Zainali, S. Ma Lu, Y. Bellone, P.E. Campana, Optimisation of agrivoltaic systems within the water-energy-food nexus, Journal of Cleaner Production 538 (2026) 147275. https://doi.org/10.1016/j.jclepro.2025.147275.

[6] M. Trommsdorff, M. Vorast, N. Durga, S. Padwardhan, Potential of agrivoltaics to contribute to socio-economic sustainability: A case study in Maharashtra/India, AIP Conf. Proc. 2361 (2021) 040001. https://doi.org/10.1063/5.0054569.

[7] R. Waghmare, R. Jilte, S. Joshi, P. Tete, Review on agrophotovoltaic systems with a premise on thermal management of photovoltaic modules therein, Environ Sci Pollut Res 30 (2023) 25591–25612. https://doi.org/10.1007/s11356-022-23202-6.

[8] L. Wang, Y. Tang, S. Zhang, F. Wang, J. Wang, Energy yield analysis of different bifacial PV (photovoltaic) technologies: TOPCon, HJT, PERC in Hainan, Solar Energy 238 (2022) 258–263. https://doi.org/10.1016/j.solener.2022.03.038.

[9] M. Sengodan, M. Suganthy, G. Ram, Effect of Different Sources of Nutrients on Productivity, Profitability and Quality of Tomato (Solanum lycopersicum L.), Madras Agricultural Journal 109 (2022) 52–59. https://doi.org/10.29321/MAJ.10.000595.

[10] A. Joseph, D. Tamilmani, Markov Chain Model of weekly rainfall probability and dry and wet spells for agricultural planning in Coimbatore in western zone of Tamil Nadu, Indian Journal of Soil Conservation 45 (2017) 66–71.

[11] V.S. Manivasagam, G.V. Saai Shreyaa, S.D. Ganesh, Food-energy-water sustainability in urban spaces: insights from open geospatial datasets in Coimbatore, India, Comput.Urban Sci. 5 (2025) 54. https://doi.org/10.1007/s43762-025-00213-w.

[12] L.P. Thyagarajan, J. Jeyanthi, D. Kavitha, Vulnerability analysis of the groundwater quality around Vellalore-Kurichi landfill region in Coimbatore, Environmental Chemistry and Ecotoxicology 3 (2021) 125–130. https://doi.org/10.1016/j.enceco.2020.12.002.

[13] J.L. Ruiz, M.D.C. Salas Sanjuan, The use of plant growth promoting bacteria for biofertigation; effects on concentrations of nutrients in inoculated aqueous vermicompost extract and on the yield and quality of tomatoes, Biological Agriculture & Horticulture 38 (2022) 145–161. https://doi.org/10.1080/01448765.2021.2010596.

[14] S. Ibrahim Abubakar, C. Hwang See, F. Muhammad-Sukki, S. Sundaram, M. Izani Zainal Abidin, M. Khairul Amri Kamarudin, Model-Based Optimization of a 10-kWp Agrivoltaic System With Semi-Transparent and Bi-Facial Panels for Enhanced Crop Yield, Energy Production, and Land-Use Efficiency, IEEE Access 13 (2025) 183755–183772. https://doi.org/10.1109/ACCESS.2025.3622476.

[15] Rajiv, M. Kumari, Protected Cultivation of High-Value Vegetable Crops Under Changing Climate, in: S.S. Solankey, M. Kumari (Eds.), Advances in Research on Vegetable Production Under a Changing Climate Vol. 2, Springer International Publishing, Cham, 2023: pp. 229–266. https://doi.org/10.1007/978-3-031-20840-9_11.

[16] S. Touil, A. Richa, M. Fizir, B. Bingwa, Shading effect of photovoltaic panels on horticulture crops production: a mini review, Rev Environ Sci Biotechnol 20 (2021) 281–296. https://doi.org/10.1007/s11157-021-09572-2.

[17] K. Mehta, W. Zörner, Optimizing Agri-PV System: Systematic Methodology to Assess Key Design Parameters, Energies 18 (2025) 3877. https://doi.org/10.3390/en18143877.

[18] Y. Bellone, M. Croci, G. Impollonia, A. Nik Zad, M. Colauzzi, P.E. Campana, S. Amaducci, Simulation-Based Decision Support for Agrivoltaic Systems, Applied Energy 369 (2024) 123490. https://doi.org/10.1016/j.apenergy.2024.123490.

[19] Y. Bellone, Approaches to Plan and Deploy Sustainable Agrivoltaic Systems, (2026). https://tesidottorato.depositolegale.it/handle/20.500.14242/365048 (accessed August 15, 2026).

[20] Z. Ghaffarpour, M. Fakhroleslam, M. Amidpour, Calculation of energy consumption, tomato yield, and electricity generation in a PV-integrated greenhouse with different solar panels configuration, Renewable Energy 229 (2024) 120723. https://doi.org/10.1016/j.renene.2024.120723.

[21] K. Bao, L. Kalisch, T. Santhanavanich, D. Thrän, B. Schröter, A bottom-up GIS-based method for simulation of ground-mounted PV potentials at regional scale, Energy Reports 8 (2022) 5053–5066. https://doi.org/10.1016/j.egyr.2022.03.187.
[22] H. Ding, S. Tao, L. Zhang, Y. Li, X. Wu, J. Zhang, J. Guo, E. Bao, K. Cao, Optimization Design of Agrivoltaic Systems Based on Light Environment Simulation, Agriculture 15 (2025) 2437. https://doi.org/10.3390/agriculture15232437.
[23] C.F. Luna-Carlosama, F.N. Jiménez-García, Impact of Agrivoltaic System Design on Productivity and Sustainability: A Systematic Review and Bibliometric Analysis, World 7 (2026) 71. https://doi.org/10.3390/world7050071.
[24] R.A. Ferreira Junior, I.C. Torres, L.F.L. de Souza, M.A. dos Santos, M.A.A. Cavalcante, C. Tiba, J.L. de Souza, Agrophotovoltaic systems in sugarcane crop – A Brazilian case study, Energy Conversion and Management 344 (2025) 120307. https://doi.org/10.1016/j.enconman.2025.120307.
[25] J.A. Duffie, B. William A, Solar Engineering of Thermal Processes, 2013. https://doi.org/10.1002/9781118671603.
[26] B.Y.H. Liu, Jordan, Daily Insolation on Surfaces Tilted towards the Equator., ASHRAE J (1961). https://www.osti.gov/biblio/5047843 (accessed August 15, 2026).
[27] M. Koehl, M. Heck, S. Wiesmeier, J. Wirth, Modeling of the nominal operating cell temperature based on outdoor weathering, Solar Energy Materials and Solar Cells 95 (2011) 1638–1646. https://doi.org/10.1016/j.solmat.2011.01.020.