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Annual Growth Analysis Of Standalone Solar Pump Adaption In India (Year 2014 To 2024).

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Abstract

India's agricultural sector is undergoing a critical energy transition, marked by a growing reliance on solar-powered irrigation systems. This study presents annual (year to year) analysis (2014– 2024) of standalone solar pump adoption in agricultural irrigation, with a central focus on the role of national renewable energy policies—particularly the Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan (PM-KUSUM) scheme. Drawing on multi-source data including government implementation reports, remote sensing analysis, and regional adoption statistics, the research evaluates the temporal change in solar pump deployment across the country. The findings demonstrate a marked acceleration in adoption rates following the scheme's rollout, supported by targeted financial incentives, land-leasing models, and grid integration mechanisms. PM-KUSUM has significantly contributed to de-dieselization, enhanced daytime power reliability, and increased farmer income through surplus energy sales. However, the study also identifies the future trend in standalone solar pump adoption across India. Overall, the analysis highlights how policy-driven interventions like PM-KUSUM can serve as catalysts for clean energy transitions in agriculture, offering a replicable framework for sustainable energy-water-agriculture nexus management in other developing economies.

Keywords: Solar irrigation, PM-KUSUM scheme, Renewable energy policy, Sustainable farming, India, Solar pump deployment.

1. Introduction:

India's agricultural sector, one of the largest in the world, is experiencing a pivotal shift in how it meets its growing energy demands. Traditionally reliant on diesel and grid electricity for irrigation, the sector is now transitioning toward solar-powered solutions. This shift is not merely technological but policy-driven—emerging from the country's broader agenda to decarbonize energy use, enhance energy access, and ensure agricultural sustainability. The past decade (2014–2024) has been particularly transformative, with the rapid deployment of solar irrigation systems reflecting both the urgency of climate goals and the strategic push of national energy policies.

Amidst concerns about greenhouse gas emissions, groundwater depletion, and rising energy costs, solar-powered irrigation has proven to be an effective intervention for addressing the energy-water-agriculture nexus. Solar irrigation technologies offer multiple benefits: reducing operational costs for farmers, improving access to daytime power for irrigation, and enabling surplus energy sales to local distribution companies (DISCOMs). These advantages align closely with national sustainable development objectives, particularly those targeting clean energy expansion (SDG 7), climate action (SDG 13), and sustainable agriculture (SDG 2).

A critical enabler of this transformation has been the introduction and implementation of dedicated policy instruments. Among these, a landmark national initiative launched in 2019 has significantly shaped the trajectory of solar pump deployment in India. Through financial incentives, infrastructure support, and flexible ownership models, this scheme has facilitated widespread adoption of decentralized solar energy technologies in the agricultural sector. Its impact can be observed in the growing number of farmers using solar pumps, the increasing capacity of solar installations on agricultural land, and the enhanced participation of rural communities in clean energy markets.

This study presents a comprehensive decadal analysis of solar energy adoption in agricultural irrigation across India. It investigates spatial and temporal trends, evaluates the influence of policy interventions, and identifies regional patterns of adoption. By leveraging implementation data, geospatial analytics, and government reports, the research assesses how well-designed policies have accelerated the integration of renewable energy into one of the most energy-intensive sectors of the economy.

The findings aim to contribute to the broader discourse on sustainable development by highlighting the role of governance in facilitating clean energy transitions. The study also provides insights into the operational and structural challenges that persist, including regional disparities in uptake, the complexities of financing models, and the trade-offs between land use for food versus energy. Ultimately, this research underscores the critical importance of coordinated policy frameworks in steering developing economies toward sustainable, resilient, and inclusive energy futures.

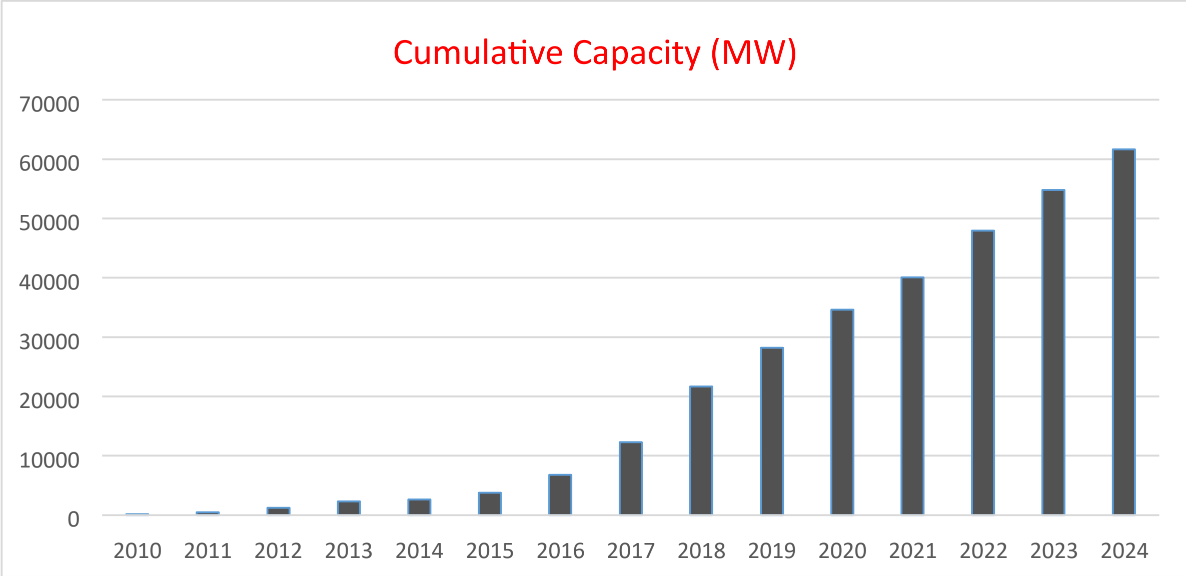

Figure 1. *Cumulative installed solar energy capacity in India (2010–2024). Data for 2022– 2024 are projections based on linear trend analysis.*

Over the last decade, India's cumulative solar energy capacity has expanded dramatically— from just 161 MW in 2010 to over 61,000 MW by 2024 (Figure 1). This surge reflects a strategic policy shift toward renewable energy, with a growing share dedicated to agricultural applications such as solar irrigation. Such a trend underscores the transformative role of targeted national policies in accelerating clean energy integration within one of India's most energy- and water-intensive sectors.

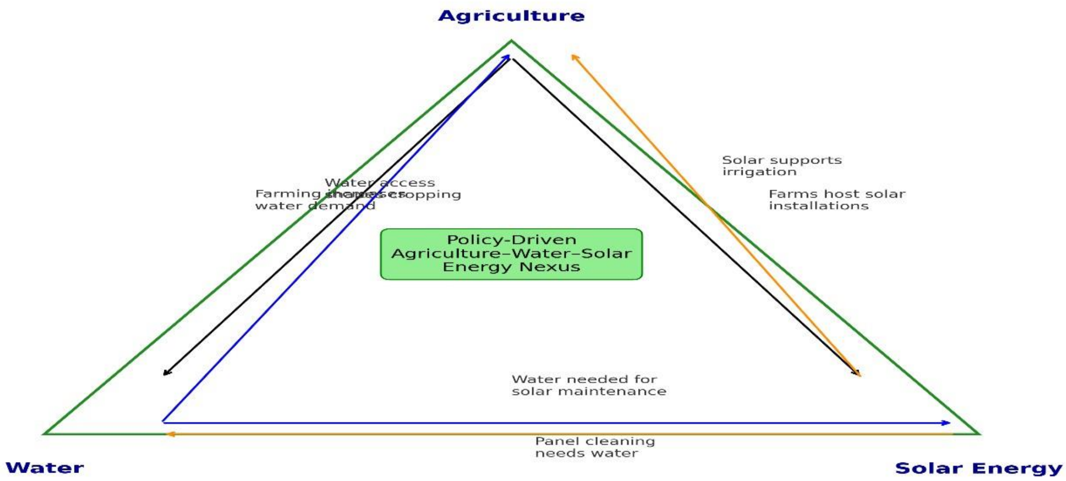

Figure 2. *Policy-Driven Agriculture–Water–Solar Energy (SAW) Nexus Illustrating Sectoral Interdependencies in the Context of Solar Irrigation in India (2014–2024)*

Over the past decade, India has witnessed a critical transition in its agricultural energy paradigm, driven by national policies aimed at decarbonizing irrigation practices and enhancing energy access in rural areas. As global greenhouse gas emissions continue to escalate, the integration of renewable energy solutions into water and agriculture systems has become imperative. Among these, solar photovoltaic (PV) technologies have emerged as a central pillar in enabling sustainable irrigation, especially through solar-powered water pumping systems, groundwater extraction, and desalination infrastructure (Kumar et al., 2022). These systems are particularly valuable in arid and semi-arid regions, where they have helped mitigate drought-related agricultural losses and improve resilience in water-scarce communities (Habib et al., 2023). Furthermore, smart irrigation tools powered by solar energy—such as sensor-based moisture monitoring—have improved water-use efficiency and enabled precision farming techniques (Hernandez et al., 2019).

At the same time, agriculture itself has facilitated the spatial expansion of solar infrastructure. Farmers across India are increasingly participating in solar adoption by leasing or allocating land for solar installations or integrating PV modules into cropping systems (Pascaris et al., 2021). This dual role of agriculture—as both energy consumer and energy enabler—supports rural income diversification and enhances the stability of decentralized power grids. However, these developments must be managed judiciously. The rapid expansion of utility-scale solar farms has raised concerns over the displacement of productive cropland, posing risks to food security, particularly in regions where arable land is limited (Carbon Brief, 2022; Sarkodie & Owusu, 2020). Environmental implications such as reduced groundwater recharge, altered microclimates, and increased water use for solar panel cleaning also highlight the need for careful site planning and policy oversight (Supe et al., 2020; Elamim et al., 2023).

Globally, agriculture accounts for about 70% of total freshwater withdrawals, and irrigated agriculture—though practiced on only 20% of cultivated land—contributes nearly 40% of the world's food production (Ingrao et al., 2023; Chowdhury et al., 2022). The higher productivity of irrigated agriculture underscores the importance of maintaining and modernizing water infrastructure while transitioning to cleaner energy sources. Nevertheless, excessive groundwater extraction continues to threaten long-term water security, necessitating improvements in irrigation governance and technology adoption (Bekele & Ancha, 2022; Huang et al., 2022). Concurrently, studies have demonstrated how renewable energy transitions are reshaping regional development trajectories, particularly in the context of population growth and urbanization (Avtar et al., 2019a, 2019b).

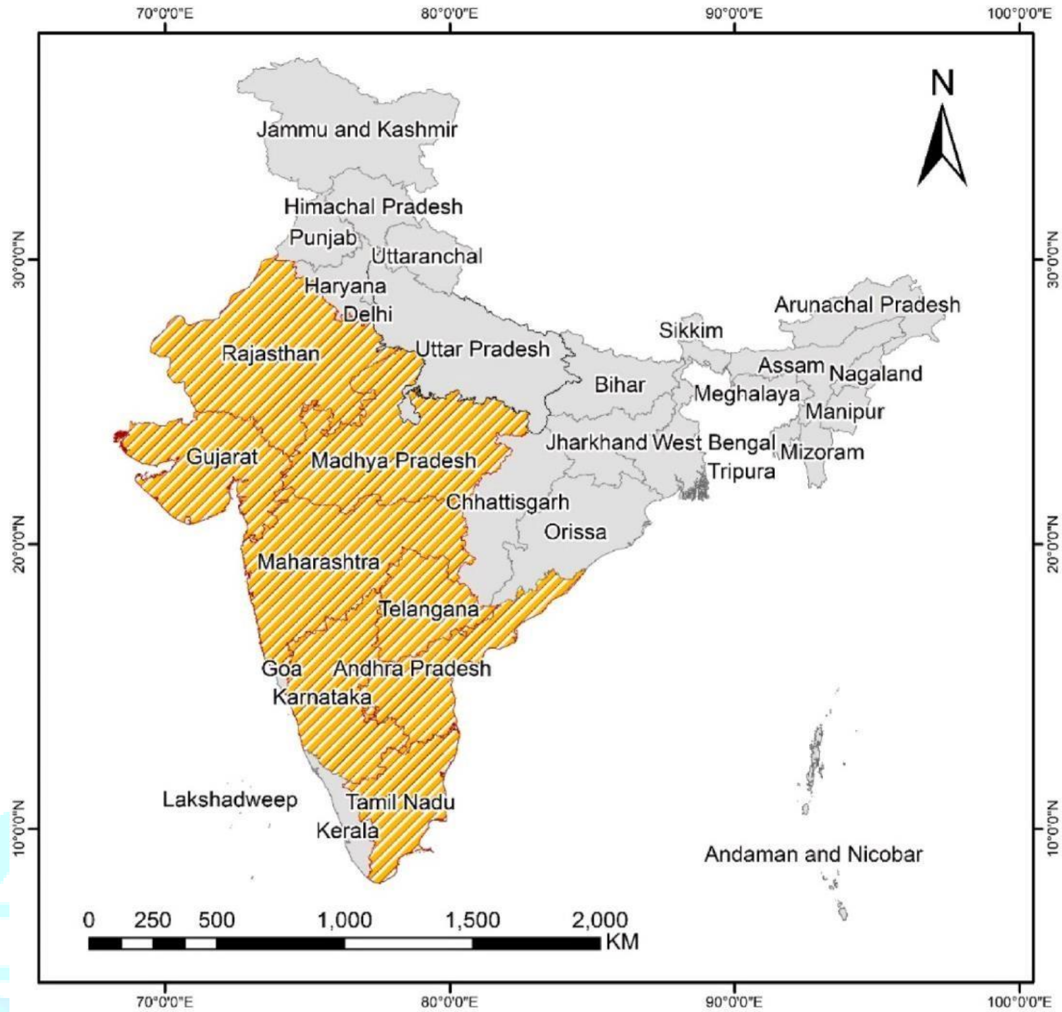

Figure 3. *Regional Concentration of Solar PV Adoption for Agricultural Irrigation in India (2014–2024)*

2. Study Area

India, located in South Asia between latitudes 8°04′N and 37°06′N and longitudes 68°07′E to 97°25′E, is characterized by a diverse agro-climatic landscape that ranges from arid deserts to fertile river basins. This geographic diversity directly influences both agricultural practices and the feasibility of solar energy deployment. The country's agriculture is largely dependent on the monsoon system, with over 75% of its annual rainfall—averaging around 1,250 mm— concentrated in the months of June to September. However, rainfall distribution is highly uneven, with certain regions like the northeastern hills receiving excess precipitation, while arid zones such as the Thar Desert in Rajasthan remain water-stressed (Pai et al., 2014). These hydrological disparities, combined with seasonal variability, present both opportunities and challenges for the integration of solar-powered irrigation systems.

Climatic conditions also play a significant role in solar energy efficiency. India's average temperature hovers around 27°C, but in semi-arid and arid regions, surface temperatures often exceed 45°C during peak summer months, leading to a notable decline in photovoltaic (PV) performance (Supe et al., 2020). Additionally, water scarcity—a persistent issue, with India ranking 133rd globally in water availability (Tayal, n.d.)—impacts not only agriculture but also the maintenance and cleaning of solar modules, particularly in dusty and drought-prone zones.

As of June 2023, India has made substantial advancements in its solar infrastructure, achieving an installed capacity of nearly 70 GW and commissioning 42 solar parks to facilitate gridconnected renewable energy development (Sahoo, 2016). This national-scale transition has been enabled by policy instruments like the PM-KUSUM scheme, which specifically targets the solarization of the agricultural sector. Regional adoption, however, has been spatially concentrated. The eight leading states—Karnataka, Rajasthan, Andhra Pradesh, Madhya Pradesh, Maharashtra, Telangana, Tamil Nadu, and Gujarat—have emerged as the primary hubs of solar irrigation, collectively accounting for approximately 87% of India's total installed PV capacity (MNRE, 2023).

These states offer optimal conditions for solar energy generation due to their high solar insolation, availability of agricultural land, and proactive state-level implementation of central schemes. Figure 3 highlights these states as the focal geography for this study, which aims to analyze the spatial and temporal diffusion of solar irrigation technologies over the past decade. The selected regions provide a representative cross-section for evaluating how national policies have driven localized adoption patterns, shaped infrastructure development, and influenced the broader energy–water–agriculture nexus in India.

3. Methodology: To investigate the decadal growth trend of standalone solar pumps for irrigation in India, this study adopted statical methodology including compound annual groth rate, year to year growth rate, polynomial regression etc. The primary objective of study was 1.To investigate growth of standalone solar pumps from year 2014 to 2024. 2. To determine the role of PMKUSUM scheme in growth of standalone solar pumps. 3. To give the future prediction of solar pumps installation. 4.To determine insallation rate of solar pumps under PMKUSUM scheme.

3.1 Compound Annual Growth Rate: The **Compound Annual Growth Rate (CAGR)** represents the **average annual growth rate** of an investment (or value like pump installations) over a period of time, assuming the growth is compounded each year.

$$\text{CAGR (\%)} = \left(\frac{\text{Ending Value}}{\text{Beginning Value}}\right)^{(1 \div t)} - 1$$

3.2 Year to year growth rate: The **Year-on-Year (YoY) Growth Rate** measures the percentage change in a value (like cumulative pumps) from one year to the next. It tells you how much the value has increased or decreased compared to the **same point one year earlier**.

The **formula used** to calculate the **Year-on-Year (YoY) Growth Rate** is:

$$\text{YoY Growth Rate (\%)} = \left(\frac{\text{Value}_{\text{current year}} - \text{Value}_{\text{previous year}}}{\text{Value}_{\text{previous year}}} \right) \times 100$$

3.3 **Polynomial Regression: It** is a form of linear regression in which the relationship between the independent variable x and dependent variable y is modelled as an *nth-degree* polynomial. Polynomial regression fits a nonlinear relationship between the value of x and the corresponding conditional mean of y, denoted E(y | x). For future prediction this test is also been used.

4. Results:

1. Growth of standalone solar water pumps and role of PMKUSUM scheme in accelerating numbers:- Over the past decade, India has experienced a considerable expansion in solar energy infrastructure in which solarisation of agriculture is a major part. We have analysed the data of standalone solar pumps from 2014 to 2024. In which year wise growth is immense in terms of numbers. Also the data of component B of PMKUSUM scheme has been added from year 2020 onwards.

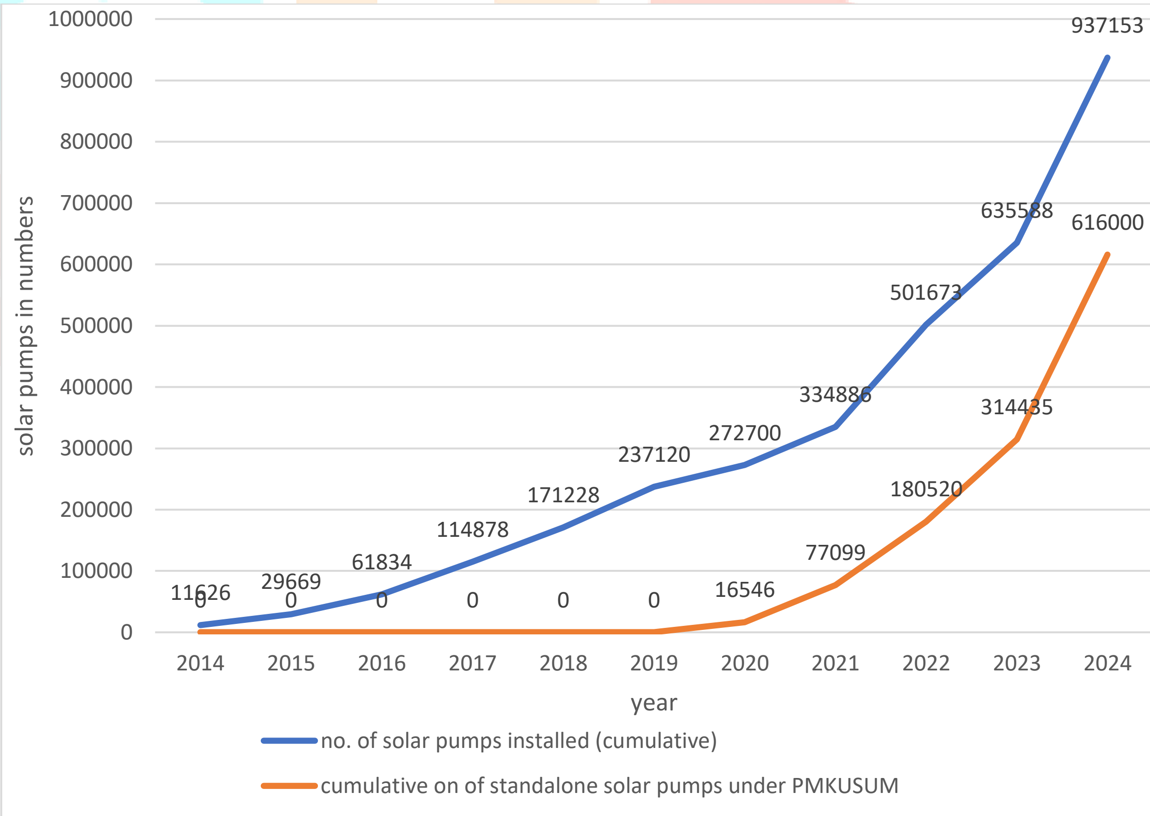

Figure 4: Increase in standalone solar pump (Cumulative)

In figure 4 continious growth is seen from year 2014 to 2024. The initial growth in standalone solar pumps was due to a central government scheme named "Jawaharlal Nehru National Solar Mission" (JNNSM). Initially it has sluggish start but it accelerated with the time. From year 2020 onwards a jump is seen in terms of numbers of solar pump installed due to PMKUSUM scheme which was initiated in 2019. From 2022 the great shift in numbers is seen due to effectiveness of PMKUSUM scheme. PM-KUSUM standalone pumps are rapidly catching up and, by 2024, account for **nearly two-thirds** of all solar pump installations in India. Sharp acceleration post-2020, especially between **2022 to 2024 due to PMKUSUM scheme.**

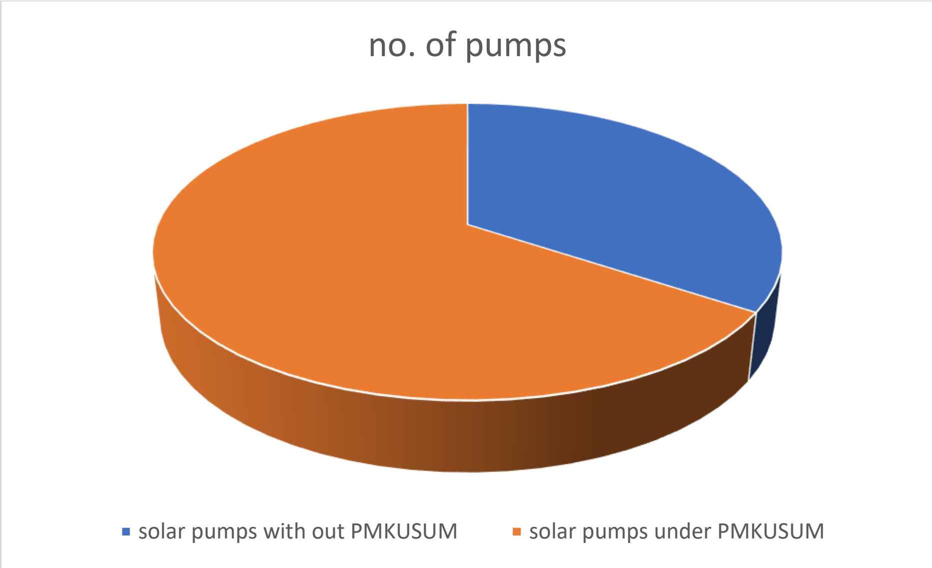

Figure 5: Pie diagram differentiating share of solar pumps under PMKUSUM and without PMKUSUM.

The **Compound Annual Growth Rate (CAGR)** of the cumulative number of pumps from **2014 to 2024** is approximately **55.11%**. This indicates a strong and consistent annual growth in pump installations over the 10-year period.

Year on year growth rate shows extremely high growth occurred between **2014 and 2016**, likely due to early expansion or adoption. Growth rates stabilized post-2019 but remained positive. Another strong rise is seen in **2024**, indicating a fresh surge, possibly linked to policy acceleration or improved implementation. This also suggest that the rate of year on year growth is declining till 2020 and it started showing slight increase afterward due to PMKUSUM scheme implications (figure 6).

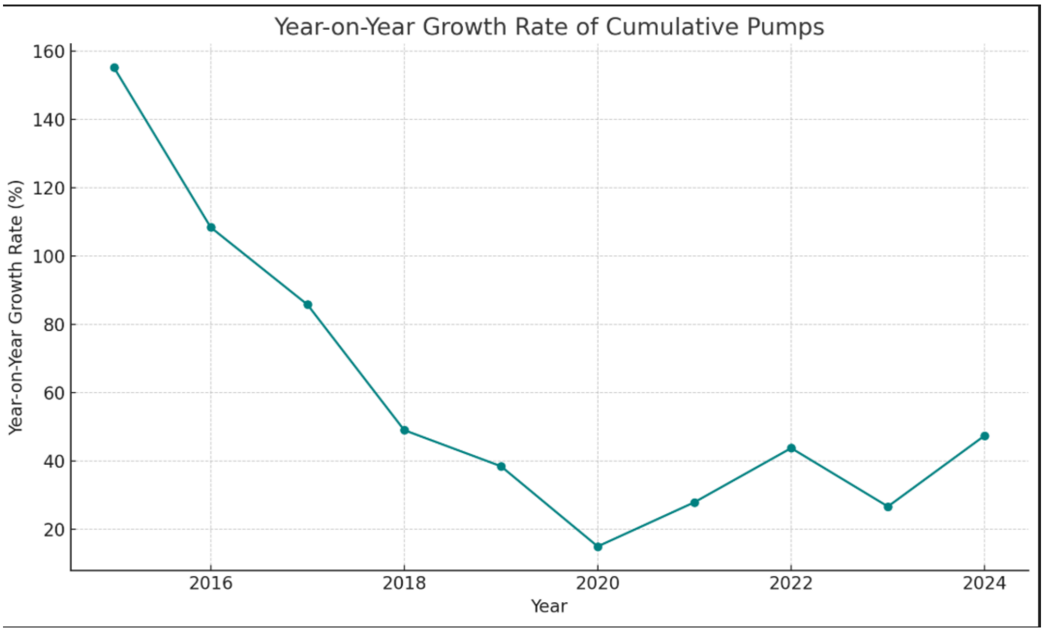

Figure 6. year on year Growth rate cumulatively.

2. Growth analysis and prediction of future trends: The polynomial regression analysis (degree 3) fits the cumulative number of pumps over the years 2014–2024.

- The cubic model captures the increasing growth rate, especially visible after 2020.
- The fit is visually good for the observed data range and shows an accelerating trend consistent with the rapid rise between 2021 and 2024.

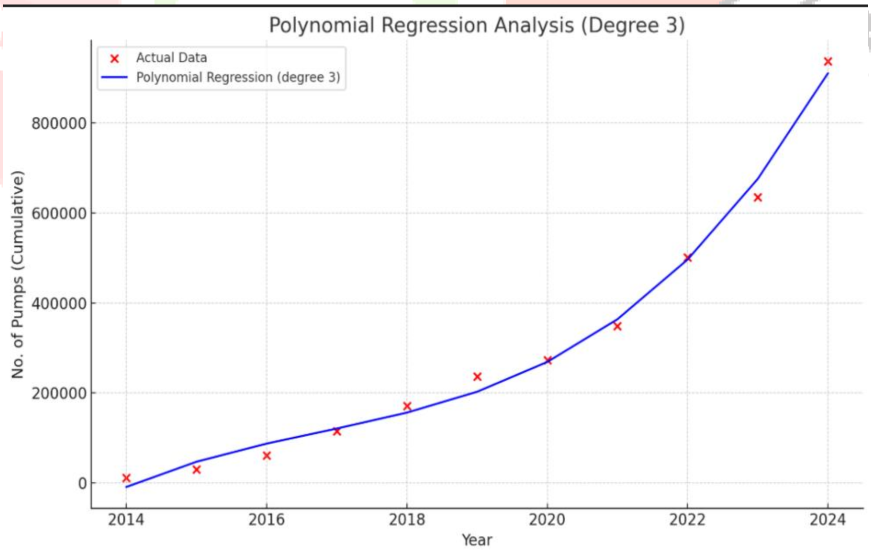

Figure 7. polynomial regression analysis of solar pumps installed in 2014 to 2024.

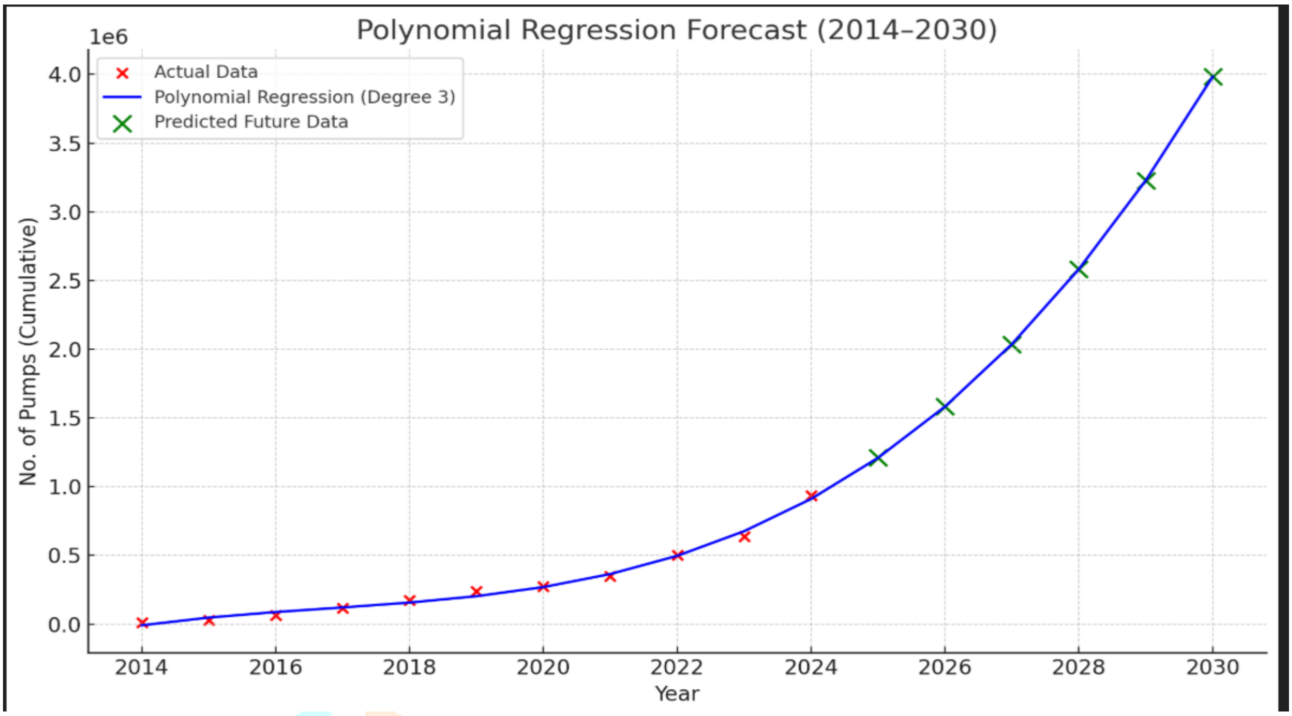

Figure 8. forecast of standalone solar pumps for coming years.

- **Red points: Actual cumulative pump data from 2014 to 2024.**
- **Blue curve: Polynomial regression model (degree 3).**
- **Green X markers: Forecasted cumulative pump numbers for 2025–2030.**

The curve indicates accelerating growth, with predictions surpassing 3.9 million pumps by 2030.

6. Conclusion:

This study examined the decadal trends in solar energy adoption for agricultural irrigation in India, emphasizing how national policies—particularly the PM-KUSUM scheme—have catalyzed a transformative shift toward renewable energy integration in the agri-energy landscape.

The analysis of solar irrigation trends from 2014 to 2024 highlights a decisive transformation in India's agri-energy sector, driven largely by proactive national policies. In particular, the **PM-KUSUM scheme** has emerged as a pivotal force in accelerating the deployment of standalone solar water pumps. The data reflects not only **steady cumulative growth** but also a **significant policy-induced surge** in installations after 2020.

The **Compound Annual Growth Rate (CAGR) of 55.11%** over the decade demonstrates strong and sustained expansion, while **year-on-year trends** show a dip in growth till 2020, followed by a renewed uptick attributed to PM-KUSUM's focused implementation. By 2024, nearly **two-thirds of all solar pumps** in India were installed under this scheme, underscoring its dominant role in driving adoption.

Polynomial regression analysis (degree 3) effectively captured this accelerating trend and forecasted a **continued rise to over 3.9 million cumulative solar pumps by 2030**, indicating a robust growth trajectory under current policy momentum.

These findings validate the central role of **well-designed, targeted policies** in scaling renewable technologies in agriculture. However, the study also flags the importance of balancing energy goals with **land, water, and food security concerns**. Going forward, the success of solar irrigation in India will depend on **integrated planning**, **cross-sector collaboration**, and **region-sensitive implementation** to ensure that clean energy adoption supports—not compromises—agricultural resilience and sustainability.

Looking forward, the sustainability of India's renewable energy transition hinges on robust, cross-sectoral policies that balance energy generation with agricultural resilience and water conservation. Targeted regulatory measures, incentives for water-efficient technologies, and prioritization of non-arable lands for solar expansion can help mitigate trade-offs. Ultimately, the findings of this study underscore that India's solar future must not come at the expense of its food and water security—but rather evolve in tandem with it, through integrated, evidence based, and policy-driven planning.

Policy Suggestions:

1. **Expand and Strengthen PM-KUSUM Implementation**
    - Continue scaling Component B (standalone solar pumps), especially in states with low adoption.
    - Simplify administrative procedures and streamline subsidy disbursement to reduce delays.
    - Increase awareness and training programs for farmers on application processes and maintenance.
2. **Promote Solar Deployment on Non-Arable and Degraded Lands**
    - Encourage solar infrastructure development on **non-cultivable or marginal lands** to avoid compromising food production.
    - Introduce land-zoning regulations that prioritize solar installations on **wastelands or canal banks**.
3. **Integrate Water-Efficient Irrigation Technologies**
    - Bundle solar pumps with **drip or sprinkler irrigation systems** to prevent over-extraction of groundwater.
    - Offer **additional incentives** for farmers who adopt both solar and water-saving technologies.

4. **Regional Customization of Subsidies and Models**
   - Customize financial incentives based on **state-level agro-climatic and socio-economic factors**.
   - In water-scarce regions, prioritize **community solar pumps** or shared infrastructure models.
5. **Mandate Environmental Impact Assessments (EIA) for Utility-Scale Solar Farms**
   - Ensure that large-scale solar installations undergo EIA to assess impact on **land, water, and biodiversity**.
   - Make **site planning and water use** for cleaning panels a regulated aspect of solar farm development.
6. **Strengthen Public-Private Partnerships (PPPs)**
   - Engage private players through **performance-linked incentives**, leasing models, and co-financing mechanisms.
   - Support start-ups offering **tech-enabled solutions** for monitoring, predictive maintenance, and irrigation scheduling.

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