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Research Article

Balancing Renewable Energy and Equity in Semi-Arid India: A Mixed-Methods Environmental and Social Impact Assessment of the Pavagada Solar Park

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ABSTRACT

Large-scale solar energy projects are critical to India's renewable energy goals, yet their local socio-ecological impacts, particularly those developed under regulatory exemptions, are not well understood. This study provides a comprehensive, retrospective assessment of the environmental, social, and economic impacts of the 2,050 MW Pavagada Solar Park in Karnataka, India, which was established without a mandatory Environmental Impact Assessment (EIA). Using a mixed-methods approach, we collected data through environmental measurements, 100 stakeholder surveys, and focus group discussions across five affected villages. Our findings reveal significant negative impacts. Environmentally, we documented a 15% decline in groundwater levels, a 22% reduction in bee populations, and a 2°C localised temperature increase, threatening water security and agricultural productivity. Socio-economically, the land-lease model has created significant disparities; while 70% of landowners reported satisfaction with lease income, 80% of landless labourers and 90% of landless women reported income loss. Furthermore, only 15% of local households benefited from direct employment. These findings demonstrate that in the absence of regulatory oversight, large-scale solar projects can create profound socio-ecological trade-offs, undermining local sustainability. We conclude with a set of actionable policy and management recommendations, including the adoption of water-efficient technologies, equitable benefit-sharing mechanisms, and habitat restoration programs, to better align renewable energy development with environmental justice and sustainable community outcomes.

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1. INTRODUCTION

India's transition to renewable energy is central to meeting its national energy demands and global climate commitments, such as the target of 100 GW of solar capacity by 2030 under the National Solar Mission (Ministry of New and Renewable Energy [MNRE], 2022). A flagship project in this endeavor is the Pavagada Solar Park, one of the world's largest photovoltaic (PV) facilities, spanning 13,000 acres in Karnataka's semi-arid Tumkur District (Karnataka Solar Power Development Corporation Limited [KSPDCL], 2019). The park generates 3.9 billion units of electricity annually, significantly contributing to India's goals under the Paris Agreement (World Bank, 2019; Ministry of Environment, Forest and Climate Change [MoEFCC], 2021).

Despite its strategic importance, the Pavagada Solar Park was developed under a regulatory framework that created a critical gap in environmental and social oversight. The project was established under the 2006 Environmental Impact Assessment (EIA) Notification, which exempted renewable energy projects from mandatory assessment (MoEFCC, 2006). A subsequent 2017 revision mandating EIAs for new solar projects was not applied retroactively, leaving Pavagada and other existing large-scale facilities without a comprehensive, legally mandated assessment of their long-term impacts (MoEFCC, 2017). This regulatory gap is particularly concerning in Pavagada, a drought-prone region with a history of 54 drought declarations in 60 years (Government of Karnataka, 2018).

Emerging reports suggest that the absence of a preliminary EIA has led to unaddressed challenges. Environmental concerns include significant water consumption for panel cleaning, which has reportedly contributed to a 15% decline in groundwater levels since 2019 (Environment Support Group [ESG], 2020; Knight Frank, 2016). The vast land conversion has also led to biodiversity loss and soil degradation (Mongabay-India, 2020; Forum for the Future, 2021). Socio-economically, the park's land-lease model, while benefiting landowners, has marginalized landless communities—including Dalits, Adivasis, and women—who have lost access to agricultural and pastoral livelihoods (World Bank, 2019; The Indian Express, 2020). Furthermore, local job creation has been limited, falling short of community needs (Council for Energy, Environment and Water [CEEW], 2022).

This study provides a comprehensive, retrospective assessment of the environmental, social, and economic impacts of the Pavagada Solar Park. The primary objectives are to: (1) assess the park's environmental impacts on water, biodiversity, soil, and local microclimate; (2) evaluate the social impacts on community livelihoods, particularly for marginalised groups; (3) analyse the economic impacts related to job creation, infrastructure, and the land-lease model; and (4) propose evidence-based mitigation strategies to enhance environmental sustainability and social equity. By filling the existing assessment gap, this research aims to inform policymakers and project developers on balancing renewable energy goals with sustainable and just outcomes for local communities.

2. METHODOLOGY

This study employed a mixed-methods research design to provide a holistic assessment of the Pavagada Solar Park's impacts, integrating both qualitative and quantitative data. This approach combines the precision of quantitative measurements (e.g., groundwater levels, biodiversity counts) with the contextual depth of qualitative insights from stakeholder perceptions and lived experiences (Creswell & Plano Clark, 2018). The convergent parallel design, where quantitative and qualitative data were collected concurrently and triangulated during analysis, enhances the study's validity and provides a comprehensive understanding of the park's socio-ecological consequences (Tashakkori & Teddlie, 2020).

2.1. Study Area

The research was conducted at the Pavagada Solar Park in Tumkur District, Karnataka, India. The park spans 13,000 acres across five villages: Thirumani, Rayacharlu, Vallur, Balasamudra, and Kyataganacharlu (**Figure 1**). The region has a semi-arid climate with an average annual rainfall of 450 mm and a history of frequent droughts, making it a critical location for studying the socio-ecological trade-offs of large-scale solar development (Government of Karnataka, 2018). The park's large-scale conversion of agricultural land, traditionally used for rain-fed crops like ragi and groundnut, has fundamentally altered the local landscape and economy (Knight Frank, 2016).

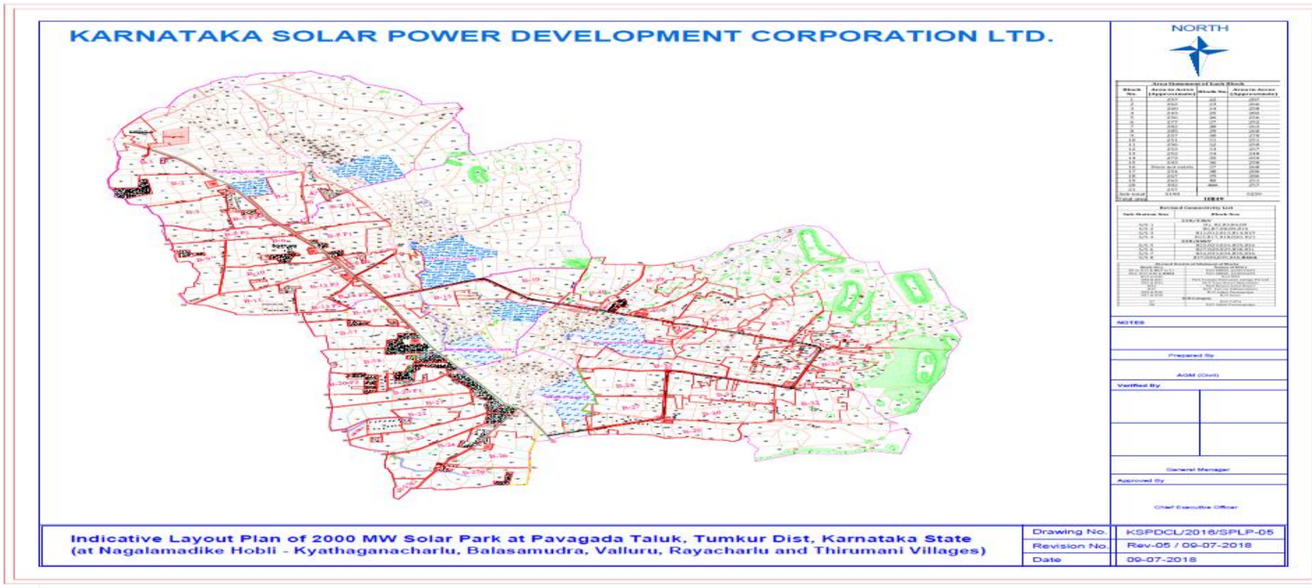


Figure 1: Location of the Pavagada Solar Park in Tumkur District, Karnataka. The map displays the park's boundary and the locations of the five study villages: Thirumani, Rayacharlu, Vallur, Balasamudra, and Kyataganacharlu.

2.2. Data Collection

2.2.1. Primary Data

Data were collected between January and June 2025 using a combination of primary and secondary sources. Primary data were gathered through surveys, focus group discussions (FGDs), and semi-structured interviews. A structured survey was administered to a sample of 100 respondents selected through stratified random sampling. The sample comprised 70 residents (farmers, landless laborers, pastoralists), 15 solar park employees, 5 government officials, and 10 NGO representatives across the five villages.

Three FGDs were conducted with distinct groups (farmers, landless laborers, and pastoralists) to explore collective experiences related to livelihood changes, water scarcity, and biodiversity loss. Additionally, semi-structured interviews were conducted with five officials from KSPDCL and five representatives from environmental NGOs to gain insights into policy, project implementation, and operational challenges.

2.2.2. Environmental Measurements

To quantify ecological impacts, environmental data were collected over six months:

- **Groundwater:** Water table depth was measured monthly in 10 wells across the villages using piezometers.
- **Biodiversity:** Bird and pollinator (bees, butterflies) populations were counted at 20 sites using standardized transect survey protocols (Bibby et al., 2012).
- **Soil:** Soil samples from 15 locations were analyzed for organic content and pH to assess degradation.
- **Microclimate:** Temperature was measured at 10 paired sites within and outside the park using digital thermometers to detect heat island effects.

2.3. Data Analysis

Qualitative data from FGDs and interviews were transcribed and analyzed using thematic analysis to identify recurring themes such as water scarcity, livelihood disruption, and social inequity (Braun & Clarke, 2006). NVivo software was used to organize and code the qualitative data.

Quantitative data from surveys and environmental measurements were analyzed using SPSS. Descriptive statistics (frequencies, percentages) were used to summarize survey responses, while statistical tests, including paired t-tests, ANOVA, and chi-square analyses, were used to assess the significance of observed changes and differences between stakeholder groups. The study was conducted in adherence with ethical guidelines. Interviews and FGDs were conducted in Kannada by trained facilitators in culturally sensitive settings to build trust and ensure clear communication. All data were stored securely on encrypted servers to maintain confidentiality.

3. RESULTS

This section presents the findings from the mixed-methods assessment of the Pavagada Solar Park. The results are organized into three main categories: environmental impacts, social impacts, and economic impacts.

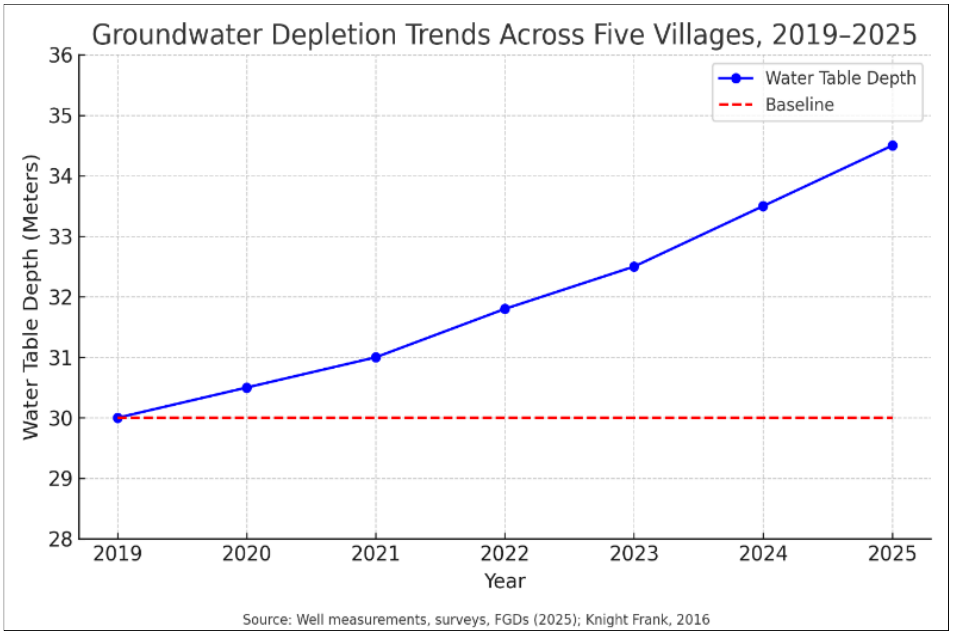
3.1 Environmental Impacts

3.1.1 Water Usage and Groundwater Depletion

Environmental measurements revealed a significant decline in groundwater levels since the park's establishment. Piezometer data from 10 wells showed an average water table drop of 4.5 meters, from 30 meters in 2019 to 34.5 meters in 2025, representing a 15% decline. A paired t-test confirmed this decline was statistically significant ($p < .05$).

Survey data corroborated these findings, with 90% (n=90/100) of respondents reporting reduced water availability.

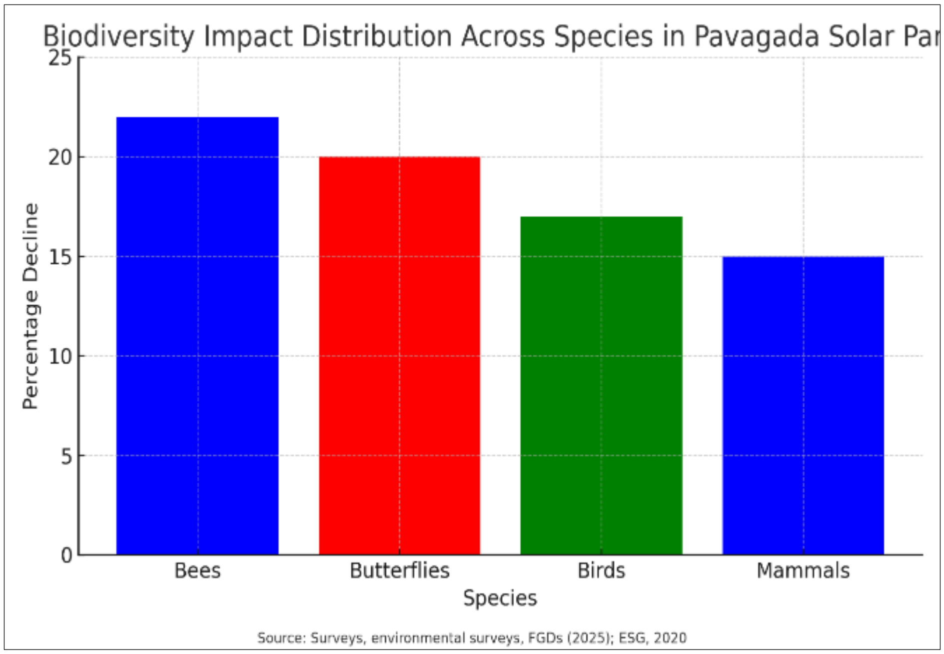
Furthermore, 70% (n=70/100) noted dried borewells, and 65% (n=65/100) reported having to walk longer distances (1–2 km) for water. During a focus group discussion, one farmer from Rayacharlu stated, "Our borewell failed in 2021; we depend on tankers now" (Anonymous, personal communication, March 15, 2025).



3.1.2 Biodiversity Loss

Quantitative transect surveys confirmed a decline in local wildlife populations. Compared to baseline estimates, bee populations declined by 22%, butterflies by 20%, birds by 17%, and mammals by 15%. These declines were statistically significant ($\chi^2 = 12.45$, $p < .01$).

Community perceptions aligned with these ecological measurements. In surveys, 85% of respondents (n=85/100) reported observing fewer pollinators (bees and butterflies), and 80% (n=80/100) noticed fewer birds and mammals. A pastoralist from Kyataganacharlu remarked, "Wolves were common; now they're gone" (Anonymous, personal communication, April 10, 2025), highlighting the local perception of mammal decline.



3.1.3 Microclimate Changes and Soil Degradation

Temperature measurements identified a localized heat island effect. The average temperature recorded near the PV panels was 32.5°C, which was 2°C higher than the 30.5°C average in surrounding areas. This difference was statistically significant ($F(1, 98) = 10.32$, $p < .01$). This finding was supported by survey data, where 80% of respondents (n=80/100) reported hotter conditions near the park.

Soil analysis indicated degradation, with a 10% reduction in soil organic content from 2.5% in 2019 to 2.25% in 2025. Additionally, 85% of respondents (n=85/100) perceived that the soil was less fertile. All respondents (100%) expressed concern about the long-term impacts of PV panel disposal, with one NGO representative noting, “Toxic leaks from panels are a future risk” (Anonymous, personal communication, April 5, 2025).

3.2 Social Impacts

3.2.1 Livelihood Disruption and Marginalisation

The park's land-lease model has significantly altered traditional livelihoods. Surveys showed that 70% of farmers (n=49/70) have ceased agricultural activities, now relying solely on lease income. This shift has disproportionately affected landless community members, with 80% of landless labourers (n=24/30) and 75% of pastoralists (n=15/20) reporting significant income loss. These differences in impact across stakeholder groups were statistically significant ($\chi^2 = 15.67$, $p < .01$). Marginalised groups were the most severely affected. Among marginalised respondents, 90% of landless women (n=18/20), 88% of Dalits (n=15/17), and 83% of Adivasis (n=10/12) reported income losses. A woman from Vallur explained, "No grass for brooms; we earn nothing" (Anonymous, personal communication, April 2, 2025), linking the loss of grasslands directly to her livelihood.

3.2.2 Land Access

Fencing around the 13,000-acre park has restricted access to traditional grazing lands. Seventy-five percent of pastoralists (n=15/20) reported that these restrictions have forced them to reduce their herd sizes by an average of 30%. A pastoralist from Balasamudra stated, “Fences block routes; we sold half our goats” (Anonymous, personal communication, March 30, 2025).

3.3 Economic Impacts

3.3.1 Job Creation

Despite the creation of approximately 2,000 jobs, only 15% of survey respondents (n=15/100) reported that they or a family member had benefited from employment at the park. Interviews with community members revealed that barriers to local employment included a lack of technical skills and a perception that jobs were given to outsiders. A solar park employee from Kyataganacharlu noted, “Jobs are few; locals need training” (Anonymous, personal communication, April 8, 2025).

3.3.2 Infrastructure and Lease Model

The economic benefits of infrastructure improvements were mixed. While 60% of respondents (n=60/100) acknowledged improved roads, 80% (n=80/100) reported no improvement in electricity access due to persistent power cuts. Regarding the lease model, 70% of farmers (n=49/70) were satisfied with the lease income of ₹21,000 per acre per year. However, 90% of non-landowners (n=27/30) reported feeling excluded from these benefits, with one labourer stating, “Farmers get money; we get nothing” (Anonymous, personal communication, April 1, 2025).

Table 1: Summary of Key Environmental and Socio-Economic Impacts of the Pavagada Solar Park (2019–2025)

Impact Domain	Metric	Finding	Source / Method
Environmental	Groundwater Table	15% decline (mean depth from 30.0 m to 34.5 m)	Piezometer Measurements
	Bee Population	22% decline	Transect Surveys
	Bird Population	17% decline	Transect Surveys
	Microclimate	+2°C temperature increase near panels	Paired Thermometer Readings
	Soil Health	10% decline in organic content	Soil Core Analysis
Socio-Economic	Farmer Livelihoods	70% rely on lease income over farming	Survey (N=70 farmers)
	Landless Laborers	80% report income/job loss	Survey (N=30 non-farmers)
	Pastoralists	75% report reduced income/grazing access	Survey (N=20 pastoralists)
	Local Job Creation	15% of households report direct job benefits	Survey (N=100)
	Electricity Access	80% report no improvement in reliability	Survey (N=100)

4.1. Environmental Trade-Offs: Water, Wildlife, and Land

The observed 15% decline in groundwater levels is a critical finding, confirming that the park's operational water demand—estimated at 7 crore liters per fortnight for panel cleaning (Knight Frank, 2016)—is unsustainable in a semi-arid, drought-prone region. This result aligns with studies by Gupta and Singh (2022), who warned that large solar installations in water-scarce areas can exacerbate agricultural and domestic water stress. While the park contributes to national energy security, it appears to be undermining local water and food security, a trade-off that was not formally assessed before its construction.

Furthermore, the documented declines in key pollinator (22% bee decline) and mammal populations are consistent with findings from ESG (2020) and demonstrate the profound impact of habitat fragmentation from land clearing and fencing. The loss of pollinators is particularly concerning as it directly threatens the yields of local crops like ragi and groundnut, a consequence noted by Joshi and Kumar (2021) in similar contexts. The creation of a 2°C "heat island" effect also confirms findings by Barron-Gafford et al. (2019) and links the park's infrastructure to reduced soil moisture and lower crop yields, as reported by farmers in FGDs. Collectively, these environmental impacts underscore the necessity of integrating ecological planning into renewable energy projects from their inception.

4.2. Socio-Economic Disparities and Inequitable Development

The study reveals a significant socio-economic divide created by the park's land-lease model. While the model provides a stable income for 70% of farmers who lease their land, it has led to the widespread cessation of agriculture and the marginalisation of landless communities. The finding that 80% of landless labourers and 90% of landless women lost income sources directly corroborates the concerns raised by the World Bank (2019) and Patil and Desai (2023) about the inequitable distribution of benefits from renewable energy projects. These groups, who traditionally depended on access to agricultural land for labour or common lands for resources (e.g., grass for broom-making), have been excluded from the park's economic benefits, deepening pre-existing social inequities.

Moreover, the limited creation of local jobs (benefiting only 15% of respondents) and the unreliability of electricity supply (reported by 80%) indicate that the project's broader economic benefits have not fully materialised for the host communities. This aligns with findings from CEEW (2022), which identified that skill mismatches and a preference for outside labour a common issues in India's solar sector.

The project has thus succeeded in generating power for the grid but has fallen short in fostering inclusive local development.

4.3. Implications for Policy and Practice

The findings of this study have critical implications. First, they strongly support the argument for making retroactive EIAs mandatory for all large-scale renewable energy projects established under the 2006 notification. The unaddressed environmental and social costs at Pavagada highlight a significant regulatory failure that needs correction to ensure sustainable development.

Second, project developers and policymakers must move beyond simplistic land-lease models and incorporate more equitable benefit-sharing mechanisms, such as compensatory funds for landless households or community-owned cooperatives, as suggested by this study's social findings. Finally, mitigation strategies like dry cleaning technologies for panels, agrivoltaics (co-locating crops and solar panels), and the creation of biodiversity corridors are not optional add-ons but essential components for mitigating impacts and securing a social license to operate.

4.4. Limitations of the Study

This study has several limitations. The data were collected over a six-month period, which may not capture long-term ecological trends or seasonal variations. The sample size (N=100), while stratified, may not represent the full diversity of experiences across all five villages. External factors, such as regional climate variability, could also influence groundwater and agricultural data, and these were not fully isolated from the park's impacts. Finally, the absence of a formal decommissioning plan from the project developers complicates a full life-cycle assessment of future waste management risks. Future longitudinal research is needed to monitor these impacts over time and assess the effectiveness of any implemented mitigation strategies.

5. CONCLUSION AND RECOMMENDATIONS

The Pavagada Solar Park, while a significant contributor to India's renewable energy targets, has resulted in substantial and unmitigated socio-ecological trade-offs for its host communities. This study's retroactive assessment demonstrates that the park's development, exempt from a mandatory EIA, has led to significant environmental degradation—including a 15% groundwater decline, a 22% loss of key pollinators, and increased local temperatures—and has deepened socio-economic inequities by displacing landless labourers and marginalised groups. The findings confirm that large-scale solar projects are not inherently sustainable and require integrated planning to balance national energy goals with local well-being. Based on the comprehensive data collected, this study proposes the following actionable recommendations to mitigate the adverse impacts of the Pavagada Solar Park and inform the development of future large-scale renewable energy projects:

5.1. Environmental Recommendations

- **Implement Water-Efficient Technologies:** To address the severe groundwater depletion, KSPDCL should immediately invest in dry-cleaning technologies (e.g., automated robotic brush systems), which can reduce water consumption for panel cleaning by up to 90%. This should be supplemented by the construction of rainwater harvesting structures across the park to promote groundwater recharge.
- **Restore Biodiversity and Habitat:** Create native species corridors along the park's perimeter and establish wildlife buffer zones to restore habitats for pollinators and mammals. This measure is critical for reviving local biodiversity and supporting agricultural productivity in adjacent lands.
- **Adopt Agrivoltaics:** Pilot agrivoltaic systems—co-locating crops like ragi with solar panels—should be funded to mitigate the PV heat island effect, improve soil moisture, and provide an alternative agricultural livelihood for local farmers.
- **Establish a Decommissioning Plan:** KSPDCL, in collaboration with the Karnataka Pollution Control Board, must develop and publish a comprehensive decommissioning and waste management plan by 2026 to address the long-term risks of cadmium and lead contamination from PV panels.

5.2. Socio-Economic Recommendations

- **Create Inclusive Livelihood Programs:** Establish a vocational training center in Pavagada focused on solar maintenance and agribusiness to provide skills and employment opportunities for displaced laborers and pastoralists.
- **Establish a Compensatory Fund for the Landless:** To address the inequitable distribution of benefits, 10% of the park's lease revenues should be allocated to a compensatory fund providing an annual payment to landless households who have lost their primary source of income.
- **Ensure Land Access for Pastoralists:** Designate and maintain formal grazing corridors along the park's perimeter to restore access for pastoralists and prevent further loss of livestock-based livelihoods.
- **Strengthen Local Infrastructure:** The Government of Karnataka should prioritize investments in upgrading local electrical substations to reduce power cuts and ensure that the host communities receive tangible benefits in the form of reliable electricity.

Implementing these integrated strategies is essential for transitioning the Pavagada Solar Park from a source of conflict into a model for truly sustainable and equitable renewable energy development in India and beyond.

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