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Solar energy potential, spatial suitability, and existing solar infrastructure in Ladakh, India

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Abstract

Ladakh, located in the trans-Himalayan region of northern India, is widely recognized as the "Solar Capital of India" due to its high altitude, low cloud cover, and exceptionally high solar insolation. The region receives average solar radiation ranging from 5.5 to 7.0 kWh/m²/day with more than 300 clear sunny days annually, making it one of the most solar-rich regions in the country. This study assesses the solar energy potential of Ladakh, identifies spatially suitable regions for solar energy deployment, and evaluates the current status of grid-connected, off-grid, and decentralized solar energy infrastructure. Using secondary data from MNRE, SECI, LREDA, KREDA, ISPRS, and published reports, the study highlights Ladakh's capacity for utility-scale solar parks as well as decentralized systems that enhance local energy security. The findings indicate that while Ladakh possesses exceptional natural advantages for solar power generation, challenges related to terrain, winter snow cover, operation and maintenance, and grid integration continue to influence scalability. The study concludes that a multi-scalar and hybrid renewable energy approach is essential for sustainable energy transition in this ecologically sensitive high-altitude region.

Keywords: Solar energy, Ladakh, solar insolation, renewable energy, decentralized solar, high-altitude regions

Introduction

Ladakh region, which falls in the trans-Himalayan region of northern India, is usually known as the "Solar Capital of India" because of its distinct geographical and climatic conditions. The region is at an altitude of more than 3,000 meters above mean sea level, with thin atmospheric layers, low humidity, and low cloud cover. These conditions permit high intensities of solar insolation, 5.5–7.0 kWh/m²/day, which is one of the highest in India and comparable to some of the world's best solar-rich areas. There are more than 300 clear sunny days in a year, and Ladakh offers a unique natural advantage for solar energy harvesting on a large and small scale. Traditionally, Ladakh's energy profile has been characterized by geographical remoteness and harsh climatic conditions. Over several decades, traditional communities have generated basic energy requirements from diesel generators, kerosene, fuelwood, and small hydropower schemes. These resources, however, have severe constraints: Diesel generators are economically expensive because of high transportation costs of fuel and environmentally toxic emissions. The use of fuelwood leads to forest degradation in sensitive eco-systems, compromising biodiversity. Hydropower schemes are operationally challenged during the cold winter seasons, when rivers and streams freeze. Consequently, energy insecurity has continued, hampering socio-economic development and subjecting the region's vulnerable ecology to added stress. In this situation, solar power presents the most feasible alternative, providing a means of attaining sustainable energy security while at the same time solving the region's environmental and development issues. By moving to solar-based systems, Ladakh can cut its reliance on fossil fuels, reduce greenhouses gas emissions, and supply reliable and low-cost electricity to far-flung villages. Notably, the use of solar power can also spur socio-economic development through the creation of employment opportunities, encouraging clean industries, and enhancing quality of life in off-grid villages.

This research work, therefore, aims to provide a comprehensive assessment of solar energy in Ladakh by exploring the following dimensions: Solar Energy Potential, Suitable Regions for Deployment, Current Solar Infrastructure and Performance, Efficiency & Scalability. Through the exploration of these dimensions, this study chapter positions solar energy as much a technological fix as a cornerstone of sustainable development, mediating the energy-environment-development nexus in one of India's ecologically most vulnerable and strategically most important regions

Review of Literature

Solar energy development in cold desert and high-altitude regions has received increasing academic and policy attention due to the growing demand for clean energy and the vulnerability of mountain ecosystems. Ladakh, owing to its high elevation, clear-sky conditions, and low atmospheric attenuation, has been repeatedly identified as one of India's most promising regions for solar power generation (MNRE, 2023; Solargis, 2021) [11, 14]. Several studies have highlighted that high-altitude regions receive greater global horizontal irradiance compared to lowland areas due to reduced aerosol concentration and thinner atmospheric layers (Duffie & Beckman, 2013; Sengupta *et al*., 2018) [4, 12]. In the Indian context, the National Institute of Solar Energy (NISE) and MNRE have classified Ladakh among the highest solar potential zones, with annual average solar radiation exceeding 5.5 kWh/m²/day, which is significantly higher than the national mean (MNRE, 2023).

Research focusing specifically on Ladakh indicates that the region's cold desert climate enhances photovoltaic efficiency by reducing thermal losses associated with high module temperatures (ICAR, 2017; Down to Earth, 2022) [3]. However, winter snowfall and prolonged snow cover have been identified as major constraints affecting seasonal power generation and system maintenance (Shukla *et al*., 2016) [13]. Studies emphasize the need for region-specific design adaptations, including optimized panel tilt angles, tracking systems, and regular cleaning mechanisms to mitigate snow-related losses (IRENA, 2020). Spatial suitability analyses using GIS and remote sensing techniques have been widely applied to identify optimal solar installation zones in mountainous regions. ISPRS-based studies demonstrate that parameters such as solar insolation, slope, aspect, land cover, and proximity to infrastructure are critical for solar site selection in fragile landscapes like Ladakh (ISPRS, 2022) [3]. Similar multi-criteria approaches have been adopted in other Himalayan regions, reinforcing the applicability of zonation-based planning for renewable energy deployment (Charabi & Gastli, 2011) [1].

From an infrastructure perspective, literature highlights the importance of decentralized solar systems in improving energy access in remote and sparsely populated regions. Studies from Ladakh and comparable mountain environments show that solar microgrids, solar thermal systems, and household-level photovoltaic applications significantly reduce dependence on diesel generators and biomass fuels, while improving social indicators such as education, healthcare access, and livelihood resilience (LREDA, 2022; CDKN, 2021). Solar greenhouses and solar water heating systems have been particularly effective in addressing food security and domestic energy needs in high-altitude cold climates (ICAR, 2017).

At the policy level, SECI and MNRE reports emphasize Ladakh's strategic importance in India's renewable energy transition, particularly through the development of utility-scale solar and hybrid renewable energy parks aimed at national grid supply (SECI, 2023) [9]. However, existing literature also points to challenges related to ecological sensitivity, land-use conflicts, transmission infrastructure, and project implementation delays in large-scale renewable projects in Himalayan regions (Rajya Sabha Secretariat, 2023 [10]; IRENA, 2020).

Overall, the existing body of literature establishes that Ladakh possesses exceptional solar energy potential supported by favourable climatic conditions, but sustainable deployment requires a balanced approach that integrates large-scale grid-connected projects with decentralized and community-oriented systems. The present study builds upon this literature by synthesizing solar potential assessment, spatial suitability, and existing infrastructure within a single analytical framework for Ladakh.

Solar Energy Potential in Ladakh

The assessment of solar radiation across Ladakh reveals consistently high insolation values, ranging from 5.2 to 6.0 kWh/m²/day, with peak radiation exceeding 7.0 kWh/m²/day in several locations. Areas such as Leh, Hanle–Nyoma, and Pang–Debring–Kharnak exhibit some of the highest solar radiation levels recorded in India. Leh records an average solar radiation of 5.54 kWh/m²/day, with peak values of 7.0–7.5 kWh/m²/day at a tilt angle of 35°, supported by over 320 clear days annually. Kargil, though slightly lower due to its valley setting, still receives 5.2–5.5 kWh/m²/day with more than 300 clear days per year, making it suitable for medium-scale solar installations. The Hanle–Nyoma region demonstrates the highest solar potential, with average radiation between 5.6 and 6.0 kWh/m²/day and minimal human habitation, leading to its designation as a solar hotspot by MNRE and SECI.

These findings confirm that Ladakh ranks among the most solar-rich regions in India, comparable to globally renowned solar zones such as the Atacama Desert and North Africa. The spatial heterogeneity of solar resources necessitates region-specific planning strategies to optimize deployment at multiple scales.

Table 1: Average Solar Insolation in Ladakh

Location	Average Solar Radiation (kWh/m²/day)	Peak Radiation (kWh/m²/day)	Clear Days per Year	Remarks
Leh	5.54	7.0–7.5 (tilted 35°)	320+	Highest in J&K region
Kargil	5.2–5.5	6.8–7.2	300+	Lower than Leh due to valley setting
Hanle–Nyoma (Eastern Ladakh)	5.6–6.0	>7.0	320+	Declared as solar hotspot by MNRE/SECI
Pang–Debring–Kharnak (Leh)	5.5–5.8	>7.0	310+	Selected for large hybrid RE park

Sources: ISPRS Archives (2022) [7]; ICAR Journal (2017); MNRE & SECI reports (2023); Solargis Atlas (2021) [14].

Spatial Suitability for Solar Energy Deployment

The suitability of different regions in Ladakh for solar energy deployment depends not only on solar radiation but also on land availability, accessibility, transmission infrastructure, and socio-environmental conditions. The Hanle–Nyoma and Pang–Debring–Kharnak plateaus exhibit excellent suitability due to vast expanses of barren land, sparse population, and high insolation, making them ideal for large utility-scale and hybrid renewable energy parks.

Kargil's Suru Valley presents high suitability for medium-scale projects (50–100 MW) due to moderate land availability and proximity to existing transmission infrastructure. In contrast, areas such as Tangtse–Durbuk and Rangdum (Zanskar) are more suitable for decentralized and community-based solar systems because of limited flat terrain and remoteness. This spatial differentiation highlights the need for a multi-scalar deployment strategy that integrates large grid-connected projects with decentralized systems to ensure both national energy contributions and local energy access.

Table 2: Suitability of Different Regions for Solar Deployment

Region	Key Features	Land Availability	Suitability Level	Planned/Existing Projects
Hanle–Nyoma	Highest insolation, remote desert	20,000+ acres of barren land	Excellent	10 GW solar park planned
Pang–Debring–Kharnak	High insolation, sparse population	Vast grazing/desert land	Excellent	13 GW RE hybrid park proposed
Kargil (Suru Valley)	Good radiation, closer to transmission	Moderate land availability	High	50–100 MW projects planned
Tangtse–Durbuk	Near habitations, microgrids feasible	Limited flat land	Moderate	Community microgrids
Rangdum (Zanskar)	Excellent insolation, but highly remote	Rugged terrain	Medium	Monastery-scale systems

Sources: MNRE (2023); SECI project documents; ISPRS (2022); Dialogue.earth (2021).

Existing Solar Energy Infrastructure

Solar energy infrastructure in Ladakh includes grid-connected projects, decentralized off-grid systems, and solar thermal applications. The Taru Solar PV project in Leh, with a capacity of 25 MW (AC) supported by 40 MWh battery storage, represents Ladakh's first major solar-plus-storage initiative. Additionally, a 13 GW hybrid renewable energy park combining solar, wind, and storage has been proposed for the Pang–Debring–Kharnak plateau. In Kargil, proposed solar PV projects ranging from 50–100 MW are at the feasibility stage, aimed at reducing diesel dependency and enhancing regional energy self-reliance. Decentralized systems, including solar microgrids, monastery-scale installations, solar greenhouses, solar water heaters, and solar cookers, play a critical role in serving remote communities. Solar thermal initiatives under the Ladakh Renewable Energy Initiative (LREI) have achieved full execution across categories, including solar greenhouses, water heating systems, and community solar cookers, significantly improving winter livelihoods, food security, and household energy efficiency.

Table 3: Grid-Connected Solar Projects

Project	Capacity	Technology	Status	Implementing Agency
Taru Solar PV (Leh)	25 MW ac (50 MW dc) + 40 MWh storage	PV + Battery	Under construction	SECI / Prozeal Green
Hybrid RE Park (Leh)	~13 GW (Solar + Wind + Storage)	Utility-scale	Planned	MNRE + SECI
Kargil Solar PV Projects	50–100 MW	PV	Feasibility stage	MNRE

Sources: Indus Dispatch (2024); PIB (2023); SECI tenders.

Performance, Efficiency, and Scalability

Ladakh's cold desert climate enhances photovoltaic efficiency by reducing module overheating, resulting in higher energy yields per installed capacity. However, winter snowfall poses operational challenges by obstructing panel surfaces, necessitating regular maintenance, cleaning, and appropriate tilting mechanisms.

Table 4: Off-grid and Decentralized Solar Projects

Initiative	Capacity / Coverage	Beneficiaries	Implementing Agency
Solar Microgrids (Tangtse, Leh villages)	50–200 kWp each	~350 households per microgrid	LREDA + NGOs
Rangdum Monastery Solar	Small PV system	Monastic community	NGO-based
Solar Greenhouses	~3,000 units	Farmers	LREDA
Solar Water Heaters	Installed in ~40% Leh households	Domestic heating	LREDA
Solar Cookers/Driers	4,500 units	Rural households	LREDA

Sources: LREDA Annual Report (2022); CDKN (2021); Reach Ladakh (2023) [2, 8, 10].

Off-grid systems have demonstrated reliability but face challenges related to operation and maintenance, particularly battery replacement and technical support. Grid-connected mega-projects, although ambitious, continue to experience delays due to policy coordination issues, environmental sensitivities, and transmission constraints. Despite these challenges, Ladakh's high irradiance, abundant sunshine days, and favorable temperature regime position it as a highly viable region for long-term solar energy development.

Conclusion

Ladakh possesses one of the highest solar energy potentials in India, supported by exceptional climatic conditions and extensive non-agricultural land availability. Decentralized solar initiatives have already contributed significantly to rural electrification, livelihood enhancement, and environmental sustainability. However, the realization of large-scale solar ambitions depends on effective policy implementation, improved grid integration, and adoption of hybrid renewable technologies. A balanced approach combining utility-scale solar parks, hybrid systems, and decentralized microgrids is essential to ensure energy security, ecological sustainability, and socio-economic development. If effectively implemented, Ladakh can emerge as both an energy-independent region and a major contributor to India's renewable energy transition.

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