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Towards a carbon-neutral and climate-resilient Ladakh: A systematic review of solar energy pathways and policy frameworks

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Abstract
This systematic review examines technological innovations, policy frameworks, solar energy pathways, and governance challenges for transitioning Ladakh toward climate resilience and carbon neutrality. Ladakh's exceptional solar irradiance (7-7.5 kWh/m²/day), coupled with fragile ecosystems, winter deficits, diesel dependence, and positions it as a critical testbed for decentralized floating solar, thermal systems, solar Photo-Voltaic, and cogeneration technologies like transcritical CO_2 cycles. Drawing on diverse sources including policy roadmaps (TERI 2021), technical energy dynamics analyses (Abdul Rahim & Sharma 2024), assessments (Santra 2015; Divine Sharon *et al*. 2023), and critical perspectives (Joshi & Kothari 2024) the review highlights tensions between community-led solutions and centralized mega-projects, while advocating pluriversal, context-specific strategies aligned with India's National Solar Mission. Key findings underscore the need for socio-ecological justice, energy storage, institutional reforms and hybrid renewables to overcome political barriers, economic, and infrastructural offering a roadmap for sustainable energy in high-altitude region Ladakh.

Keywords: Cold desert, solar photovoltaics (PV), carbon-neutral Ladakh, fragile ecosystem, National Solar Mission

Introduction

Ladakh, a high-altitude cold arid region in the Indian Trans-Himalaya, is emerging as a strategically important laboratory for renewable and particularly solar-led energy transitions, where extreme climatic conditions coexist with exceptional solar irradiance and fragile mountain ecosystems. Against the backdrop of India's broader low-carbon agenda and ambitious solar targets under national missions, Ladakh's energy debate has shifted from mere electrification toward questions of sustainability, autonomy, and socio-ecological justice, as reflected in recent technical, policy, and human-geography scholarship on the region. Existing literature documents how the Union Territory combines abundant solar resources and growing renewable infrastructure with persistent winter deficits, diesel dependence, and climate vulnerability, prompting a re-examination of centralized mega-projects versus decentralized, community-oriented solutions. At the same time, national and global reviews on solar energy technologies, business feasibility, and renewable potential highlight both the technological maturity of solar photovoltaics and solar thermal systems and the need for context-specific strategies in remote, high-altitude regions such as Ladakh, where energy planning must navigate infrastructural constraints, harsh environmental conditions, and evolving development aspirations.

Solar Energy Perspectives: Global and National Level

The study by Santra (2015) [10], published in Annals of Arid Zone, provides a clear and academically robust assessment of the scope and relevance of solar energy in the cold arid region of Ladakh. The paper effectively situates Ladakh's energy scenario within the broader national renewable energy framework, particularly the targets of the National Solar Mission, while highlighting the region's acute dependence on diesel-based power generation and its associated economic and environmental costs. A major strength of the study lies in its detailed analysis of solar irradiance, demonstrating that Ladakh receives exceptionally high solar radiation (7–7.5 kWh/m²/day), far exceeding the national average, which makes solar energy the most technically viable and sustainable option for meeting future power demands. The author convincingly argues that centralized grid extension is neither feasible nor economical for remote and high-altitude settlements, thereby underscoring the importance of decentralized and off-grid solar systems. The paper also acknowledges the institutional role of the Ladakh Renewable Energy Development Agency in promoting non-conventional energy technologies and emphasizes complementary measures such as energy efficiency and LED adoption. Overall, the study offers a well-grounded, policy-relevant, and region-specific analysis, making it a valuable reference for research and planning on renewable energy and sustainable development in cold arid environments like Ladakh.

Database & Methodology

The database for this review work comprises peer-reviewed articles, books, and policy documents sourced from reputed Scopus, web of sciences, UGC care journals, proceedings, and reports, spanning 2015-2025, with a due-focus on Ladakh-specific and national/global contexts. To achieve the prime objective of the study methodology follows systematic review principles: thematic synthesis of sustainability dimensions, governance, economic, technical; comprehensive literature search via academic databases, inclusion based on relevance to solar pathways/policies in

cold-arid/high-altitude settings, and critical appraisal of gaps/strengths, empirical vs simulation-based studies.

Renewable Energy Developments in Ladakh

Brief Study on Installation of Floating Solar Power Plant for Sustainable Energy Generation at Ladakh" (2023) Published in Materials Today: Proceedings, Vol. 90 (Part 1), pp. 305–310. The study by Divine Sharon *et al*. (2023) [2] presents a concise yet technically meaningful assessment of the potential of floating solar photovoltaic (FSPV) systems for sustainable energy generation in Ladakh, a region characterized by remoteness, harsh climate, and increasing energy demand. The paper effectively contextualizes Ladakh's energy challenges following its transition into a Union Territory, highlighting long transmission distances, frequent power outages, and heavy dependence on diesel generators and small hydropower plants. A key academic strength of the study lies in its justification of localized renewable energy systems as a practical alternative to centralized grid expansion in high-altitude and disaster-prone terrain. By introducing FSPV technology—originally developed in Japan and now gaining global traction—the authors argue that water bodies in and around Leh offer underutilized surfaces for clean energy generation while minimizing land-use conflicts, which are particularly acute in mountainous regions. The paper clearly explains the technical concept of floating solar systems, including mooring, anchoring, and operational advantages such as improved panel efficiency due to cooling effects of water and reduced evaporation losses. Although the study is preliminary in nature and does not include detailed techno-economic modeling or long-term performance analysis under extreme cold conditions, it successfully establishes the feasibility and strategic relevance of floating solar power in Ladakh. Overall, the paper contributes valuable early-stage insights and serves as a useful reference for future research and policy planning on innovative solar technologies in cold arid and high-altitude regions.

Energy Dynamics and Sustainability in Ladakh: A Comprehensive Analysis of Renewable Resources, Consumption Patterns, and Future Strategies" International Journal of Advances in Electrical Engineering, 2024, Vol. 5(1), pp. 104–109 5-1-19-153. The paper by Abdul Rahim and Dr. Nirma Kumari Sharma (2024) [1] presents a well-structured and data-rich examination of Ladakh's energy landscape, offering a holistic understanding of renewable energy potential, electricity generation, consumption patterns, and future sustainability pathways in a high-altitude, cold-arid region. One of the major academic strengths of the study lies in its strong grounding in demographic and geographical realities, clearly showing how Ladakh's vast area, sparse population density, and predominantly rural settlement structure impose unique constraints on conventional energy infrastructure. By systematically using census data, government statistics, and institutional records, the authors establish a reliable empirical base for analyzing energy demand and supply dynamics in Leh and Kargil districts.

A significant contribution of the paper is its detailed assessment of renewable energy infrastructure, particularly hydropower, which forms the backbone of Ladakh's electricity generation system. The documentation of major hydroelectric projects such as Nimoo Basgo and Chutak, along with smaller plants managed by NHPC, the Power Development Department, KREDA, and LREDA, provides valuable insight into installed capacities, design energy, and institutional collaboration. The tabular presentation of plant-wise generation data (2018–2021) strengthens the analytical rigor and demonstrates seasonal and annual variability in power generation, highlighting the continued dependence on diesel generators during lean periods. This analysis effectively underscores both the progress made and the structural vulnerabilities within Ladakh's energy system.

The examination of electricity consumption patterns across sectors in Leh and Kargil further enhances the paper's analytical depth. By showing the dominance of domestic and commercial (including defence) sectors in electricity use, the study links energy demand to urbanization, tourism growth, and changing lifestyles. The clear regional contrast between Leh and Kargil in sectoral consumption patterns is particularly valuable, as it reinforces the argument that uniform energy policies may be ineffective and that district-specific energy planning is essential for sustainable management.

From a strategic perspective, the paper moves beyond descriptive analysis to propose future-oriented sustainability strategies, including policy interventions, technological innovation, community participation, and climate resilience. The emphasis on solar PV, small hydropower, energy storage, smart grids, and decentralized systems aligns well with Ladakh's ecological sensitivity and logistical constraints. Moreover, the focus on community-based renewable projects and capacity building adds a strong socio-economic dimension, positioning energy transition not merely as a technical shift but as a developmental and governance process.

Generally, the paper makes a substantial academic and policy-relevant contribution by integrating quantitative analysis with institutional and strategic perspectives. While the study could be further strengthened by incorporating primary field surveys or techno-economic modeling of emerging technologies such as large-scale solar and storage systems, it nevertheless succeeds in providing a comprehensive, evidence-based roadmap for Ladakh's energy transition. The paper stands as a valuable reference for researchers, planners, and policymakers working on renewable energy, sustainability, and energy security in fragile mountain and cold-arid regions, and it meaningfully contributes to the growing literature on decentralized and resilient energy systems in the Himalayas.

Solar Powered Transcritical CO_2 Cogeneration Plant for the Union Territory of Ladakh, India" (2025) *Published in* Solar Compass, Vol. 14, Article 100124. Authors: Vivek Kumar, Khalid Parra, Uday Raj Singh, and B. Satya Sekhar. The article presents a technically advanced and context-specific investigation into the feasibility of a solar-powered transcritical CO_2-based cogeneration system for Ladakh, a region characterized by extreme cold, high altitude, and fragile energy infrastructure. The study is particularly significant because it addresses Ladakh's dual energy challenge: the need for reliable electricity generation and efficient space heating under severe climatic conditions. By proposing a cogeneration plant that simultaneously produces power and usable thermal energy, the authors move beyond conventional solar PV approaches and introduce a high-efficiency thermodynamic solution tailored to cold-arid environments.

A major strength of the paper lies in its innovative use of transcritical CO_2 (sCO_2) cycles, which are well known for their compactness, higher thermal efficiency, and superior performance in low-temperature ambient conditions. The authors convincingly argue that CO_2, as a working fluid, is environmentally benign, non-toxic, and well-suited for Ladakh's temperature regime, making it preferable to conventional organic Rankine cycle (ORC) fluids. The integration of concentrated solar thermal energy with a transcritical CO_2 cycle demonstrates strong theoretical potential for improved energy conversion efficiency, reduced system losses, and enhanced operational reliability in high-altitude regions.

Methodologically, the paper is robust and grounded in thermodynamic modeling and performance analysis. The authors systematically evaluate system efficiency, power output, and heat recovery under Ladakh-specific climatic conditions, thereby ensuring regional relevance rather than generic modeling. The cogeneration framework is particularly important for Ladakh, where space heating constitutes a major share of energy demand, especially during long winters. By addressing both electrical and thermal loads, the proposed system aligns closely with real-world energy consumption patterns in the region.

From a sustainability perspective, the study makes a valuable contribution by linking advanced solar thermal technology with decarbonization goals. The reduction in diesel dependence, lower greenhouse gas emissions, and improved energy security are clearly articulated benefits. The paper also implicitly complements existing renewable energy initiatives in Ladakh, such as solar PV and small hydropower, by proposing a dispatchable and thermally efficient alternative that can operate alongside other renewables.

However, while the paper excels in technical rigor, it remains largely simulation-based, with limited discussion on economic feasibility, capital costs, maintenance challenges, and institutional readiness for deploying such advanced systems in a remote Himalayan region. Issues related to infrastructure availability, skilled manpower, and long-term operational resilience could have been explored in greater depth. Nonetheless, these limitations do not undermine the study's core contribution, but rather highlight avenues for future applied research and pilot-scale implementation.

This article represents a high-quality and forward-looking contribution to renewable energy research in cold and high-altitude regions. By combining solar thermal energy with transcritical CO_2 cogeneration, the authors offer a novel, efficient, and climate-appropriate solution for Ladakh's energy needs. The study is particularly valuable for researchers, engineers, and policymakers interested in next-generation renewable energy systems, and it strengthens the academic discourse on sustainable, low-carbon energy transitions in extreme environments such as the Himalayan cold desert

Governance and Critical Perspectives on Ladakh's Energy Futures

Joshi, N. & Kothari, A. (2024). Autonomy and pluriversal energy futures in Ladakh, India. Human Geography, 18(6).

The article by Neelakshi Joshi and Ashish Kothari (2024), published in Human Geography, offers a theoretically rich and politically grounded analysis of energy transitions in Ladakh, situating them within broader debates on autonomy, democracy, extractivism, and socio-ecological justice. Rather than treating energy transition as a purely technical or economic process, the authors frame it as a deeply political and cultural struggle over land, resources, governance, and visions of development in a fragile trans-Himalayan region. This approach marks a significant departure from techno-centric energy studies and aligns the paper with critical human geography, political ecology, and decolonial scholarship.

A central contribution of the paper lies in its identification of two fundamentally opposing energy futures currently shaping Ladakh. On the one hand is grassroots, indigenous vision, rooted in low-impact technologies, community control, and energy sufficiency aimed primarily at local needs. On the other hand, is a state- and corporate-led technocratic vision, characterized by large-scale renewable energy infrastructure, critical mineral extraction, and the integration of Ladakh into national and global energy supply chains. The authors convincingly argue that the latter reproduces an extractive development model, treating Ladakh as a peripheral "sacrifice zone" for meeting the energy demands of distant urban and industrial centres.

The paper's analytical strength is further enhanced by its engagement with the post-2019 political reconfiguration of Ladakh and the intensification of popular movements since early 2023 demanding autonomy, constitutional safeguards, and statehood. Joshi and Kothari skillfully demonstrate how energy projects have become a focal point of political contestation, with local resistance challenging top-down decision-making, land alienation, and the erosion of customary governance systems. By linking energy transitions to constitutional and democratic questions, the authors foreground governance as a decisive factor in determining whether renewable energy pathways are socially just or extractive in nature.

Conceptually, the article makes an important intervention through the notion of "pluriversal energy futures." Drawing on decolonial thought, the authors argue against a singular, universal model of energy transition and instead advocate for multiple, place-based pathways shaped by local ecologies, cultures, and livelihoods. This framework is particularly relevant for Ladakh, where harsh climatic conditions, pastoral and agrarian livelihoods, and deep spiritual connections to land demand energy systems that are modest, decentralized, and ecologically embedded. The emphasis on democratically managed, community-run energy systems resonates strongly with broader debates on energy sovereignty and just transitions.

At the same time, the authors do not romanticize local resistance. A notable strength of the paper is its acknowledgment of internal contestations within Ladakhi society regarding development, prosperity, and modernity. The paper recognizes that aspirations for economic growth, employment, and improved infrastructure coexist with concerns over ecological degradation and cultural erosion. This nuanced treatment avoids simplistic binaries and strengthens the paper's analytical credibility.

Methodologically, while the article is primarily qualitative and interpretive—drawing on protest narratives, historical struggles, and critical policy analysis—it is well grounded in empirical realities and contemporary political developments. The lack of quantitative energy data is not a limitation but a deliberate choice, consistent with the paper's objective of re-politicizing energy transitions rather than measuring technical efficiency.

Joshi and Kothari (2024) provide a powerful and timely critique of dominant renewable energy paradigms, demonstrating that renewable does not automatically mean just or democratic. The paper significantly advances scholarship on energy transitions by foregrounding autonomy, governance, and pluriversality, and by situating Ladakh within global debates on extractivism and decolonial futures. It is an essential contribution for scholars of human geography, political ecology, development studies, and sustainability, and it offers critical insights for policymakers and planners seeking to design socially just, locally grounded, and ecologically sensitive energy futures in fragile mountain regions.

Sustainable Development Perspectives of Solar Energy Technologies with Focus on Solar Photovoltaic—A Review" Nor Izam, N. S. M., Itam, Z., Sing, W. L., & Syamsir, A. (2022) [6]. The review article by Nor Izam *et al*. (2022) [6], published in *Energies*, presents a systematic, interdisciplinary, and sustainability-oriented synthesis of global research on solar energy technologies, with a particular emphasis on solar photovoltaic (PV) systems as a cornerstone of sustainable development. The paper is firmly anchored within the framework of the United Nations Sustainable Development Goals (SDGs) and successfully positions solar energy not merely as a technological solution, but as a socio-technical pathway for addressing climate change, energy security, and environmental degradation.

A major strength of the paper lies in its holistic conceptual framing. The authors integrate environmental, health, economic, social, technical, and policy dimensions of solar energy adoption, moving beyond conventional efficiency- or cost-centric reviews. By examining the linkages between fossil-fuel-based energy systems, greenhouse gas emissions, climate change impacts, and human well-being, the study convincingly establishes the necessity of transitioning toward renewable energy, particularly solar PV, to achieve long-term sustainability. The discussion is well supported by global literature on climate change mitigation, decarbonization, and renewable energy transitions.

The review provides a clear and structured overview of the global solar energy landscape, including solar resource potential, technological evolution, and adoption trends. The authors comprehensively discuss the fundamentals of solar PV systems, including balance-of-system (BoS) components, system integration, and performance considerations across centralized and distributed applications. This technical grounding is effectively balanced with policy and governance perspectives, making the paper accessible to both engineering-focused and interdisciplinary audiences.

A notable contribution of the study is its use of the STEEP (Social, Technical, Economic, Environmental, and Policy) sustainability model, which allows for a multidimensional evaluation of solar PV technologies. Through this framework, the authors critically examine barriers to solar energy deployment, such as high initial capital costs, regulatory uncertainty, technological risks, lack of information, and market readiness. The inclusion of environmental and health barriers—often overlooked in purely technical reviews—adds significant analytical depth, especially in relation to climate change, urban emissions, and building-sector energy consumption.

The paper also establishes a strong connection between solar energy technologies and the green building movement, highlighting how PV and solar thermal systems can significantly reduce energy demand and emissions in the built environment. By reviewing international green building rating systems (such as BREEAM and LEED) and their emphasis on energy efficiency and renewable integration, the study underscores the role of solar PV in achieving low-carbon and climate-resilient infrastructure. This perspective is particularly valuable for urban planners and policymakers concerned with sustainable cities and infrastructure systems.

From a geographical perspective, the inclusion of regional case discussions, particularly from Europe and Malaysia, enhances the applied relevance of the review. The Malaysian context, in particular, is used effectively to illustrate how national policy frameworks, grid standards, and institutional support mechanisms influence solar PV adoption in tropical climates. This reinforces the argument that solar energy transitions are context-specific and must be aligned with local climatic, economic, and regulatory conditions.

Despite its much strength, the paper remains primarily conceptual and review-based, with limited quantitative comparison of lifecycle emissions, economic payback periods, or large-scale deployment scenarios across regions. However, given the stated objective of synthesizing sustainability perspectives rather than conducting techno-economic optimization, this limitation does not detract from the paper's overall contribution.

So, Nor Izam *et al*. (2022) [6] deliver a comprehensive, well-structured, and policy-relevant review that significantly advances understanding of solar photovoltaic technologies within the broader discourse of sustainable development. The paper is particularly valuable for researchers, engineers, policymakers, and planners seeking an integrated sustainability perspective on solar energy, and it serves as a strong foundational reference for future research on renewable energy transitions, green buildings, and climate-resilient infrastructure.

Carbon Neutral and Climate Resilient Ladakh: A Strategy Document – Action Plan and Roadmap (TERI, 2021) [12]. The strategy document Carbon Neutral and Climate Resilient Ladakh, prepared by The Energy and Resources Institute (TERI), presents one of the most systematic, data-driven, and region-specific roadmaps for achieving carbon neutrality in a fragile high-altitude ecosystem. Commissioned in the post–Union Territory phase, the report addresses Ladakh's unique geographical, climatic, socio-economic, and political context, positioning climate action not merely as an environmental imperative but as a developmental necessity. The document adopts an integrated vision that balances economic growth, social inclusiveness, and ecological preservation, making it a landmark policy-oriented contribution to sustainable development planning in mountain regions. A major strength of the report lies in its methodological rigor. TERI employs a combined top-down and bottom-up approach, supported by extensive stakeholder consultations, secondary data analysis, and scenario-based modelling using the LEAP (Long-range Energy Alternatives Planning) model. The formulation of two contrasting scenarios—Business-as-Usual (BAU) and an Alternate Low-Carbon Scenario—enables a clear comparison of future emission trajectories up

to 2050. This modelling framework allows the report to move beyond descriptive analysis and provide quantifiable estimates of sector-wise energy demand, emissions, and mitigation potential, thereby strengthening its policy relevance.

Sectoral analysis constitutes the core of the document. The report identifies the residential sector as the largest consumer of energy and water, with heavy dependence on fossil fuels for heating and cooking. The transport sector, driven largely by tourism growth, defence mobility, and rising private vehicle ownership, is highlighted as a rapidly expanding source of greenhouse gas emissions. Similarly, the commercial and tourism sectors are shown to exert disproportionate pressure on energy, water, and waste systems, particularly during peak summer months. The inclusion of urban management, agriculture, forestry, construction, solid waste, and defence sectors reflects the report's comprehensive scope and its recognition of cross-sectoral linkages in Ladakh's carbon footprint

One of the most significant contributions of the report is its net GHG accounting, which integrates emissions with existing carbon sinks from forests and land-use systems. The analysis reveals that while Ladakh risks becoming a net carbon emitter after 2035 under the BAU scenario, it can remain carbon-negative until 2050 if the alternate mitigation strategies are effectively implemented. This finding underscores the feasibility of carbon neutrality in Ladakh, provided that policy interventions are timely, coordinated, and adequately resourced.

The report is particularly notable for its strategic recommendations, which go beyond conventional renewable energy promotion. While large-scale solar deployment, energy storage, and grid strengthening are emphasized, equal importance is given to hydrogen-based energy systems, climate-resilient agriculture, sustainable tourism, electric mobility, green building practices, and revival of indigenous resource-management systems such as dry toilets, traditional irrigation networks, and community water governance. This reflects an understanding that carbon neutrality in Ladakh cannot be achieved through technology alone, but requires behavioral change, institutional reform, and cultural continuity.

Another key strength is the report's emphasis on climate resilience. Recognizing Ladakh's vulnerability to glacier retreat, water stress, extreme temperatures, and ecological degradation, the roadmap integrates mitigation with adaptation. Strategies for water management, sustainable agriculture, and ecosystem conservation are framed as essential for safeguarding livelihoods and long-term development, thereby aligning climate action with human security concerns.

Despite its comprehensive nature, the report acknowledges certain limitations, particularly data gaps in off-grid areas, informal tourism activities, and private groundwater extraction. However, these constraints are transparently discussed and do not undermine the overall robustness of the analysis. Instead, they highlight the need for improved monitoring systems, institutional capacity building, and continuous policy learning.

The TERI (2021) [12] strategy document represents a foundational policy framework for steering Ladakh towards a carbon-neutral and climate-resilient future. Its integrated sectoral approach, rigorous modelling, and strong emphasis on socio-ecological sustainability make it not only relevant for Ladakh but also a replicable model for other cold-arid and mountain regions facing similar development–environment trade-offs. The document serves as an essential reference for researchers, policymakers, planners, and development practitioners engaged in climate action and sustainable development in fragile ecosystems.

Goel, M., Verma, V. S., & Tripathi, N. G. (2022) [3]. Solar Energy Made Simple for a Sustainable Future.Series: Green Energy and Technology. © Springer Nature, 2022. The book Solar Energy Made Simple for a Sustainable Future by Malti Goel, V. S. Verma, and Neha Goel Tripathi (2022) [3] offers a clear, policy-relevant, and application-oriented synthesis of solar energy technologies, making it particularly valuable for regions like Ladakh, where sustainable development must be pursued under conditions of ecological fragility, remoteness, and energy insecurity. Although the book does not focus exclusively on Ladakh, its discussions on solar photovoltaics, solar thermal systems, rural energy access, and policy frameworks provide strong conceptual and practical relevance to Ladakh's solar-led energy transition.

A key strength of the book lies in its balanced treatment of technology, policy, and practice. The authors trace the historical evolution of solar energy in India and then systematically examine contemporary innovations in solar PV and solar thermal applications. This is highly pertinent to Ladakh, which possesses one of the highest solar irradiance levels in India, yet faces severe constraints in grid connectivity and fossil fuel dependence. The book's emphasis on decentralized and off-grid solar solutions aligns closely with Ladakh's settlement pattern, where dispersed rural habitations and extreme winters make centralized power systems inefficient and unreliable.

The discussion on solar applications in rural and urban contexts is especially relevant from a Ladakh perspective. The authors highlight solar home systems, solar water heating, solar lighting, and community-scale solar installations as tools for enhancing energy access and improving quality of life. These applications directly correspond to Ladakh's needs in residential heating, lighting, and institutional energy supply, where diesel-based systems have historically dominated. Moreover, the book's treatment of solar thermal technologies—often underrepresented in PV-dominated literature—is particularly significant for Ladakh, where space heating and hot water demand constitute a major share of household energy consumption.

From a sustainability standpoint, the book effectively links solar energy deployment with economic development, social equity, and environmental protection. This integrated perspective resonates strongly with Ladakh's sustainable development discourse, where energy planning must support livelihoods, reduce ecological stress, and respect local socio-cultural contexts. The authors' accessible explanations make the book suitable not only for engineers and researchers but also for policymakers, administrators, and community stakeholders involved in renewable energy planning in remote regions.

An important contribution of the book is its dedicated discussion on the International Solar Alliance (ISA), which situates India's solar ambitions within a global framework of climate-compatible development. For Ladakh, this global–local linkage is particularly important, as large-scale solar initiatives in the region are increasingly influenced by

national and international climate commitments. The book provides valuable insights into how international cooperation, technology transfer, and policy alignment can support solar expansion while advancing climate goals.

While the book excels in breadth and clarity, its treatment of extreme cold and high-altitude operational challenges remains limited. Issues such as battery performance in sub-zero temperatures, seasonal variability, and maintenance constraints in remote mountainous regions like Ladakh could have been explored in greater depth. Nevertheless, the book's strength lies in laying a foundational understanding upon which region-specific studies and adaptations can be built.

Hence, Solar Energy Made Simple for a Sustainable Future is a highly relevant and accessible reference for understanding the role of solar energy in sustainable development, particularly in solar-rich yet energy-vulnerable regions such as Ladakh. By integrating technological fundamentals, policy frameworks, and development perspectives, the book contributes meaningfully to the discourse on solar-led, inclusive, and sustainable energy transitions, and serves as a valuable resource for researchers, planners, and decision-makers working toward a clean energy future in cold and remote regions

Sharma, A., Shukla, A., & Kant, K. (2018) [11]. Perspective of Solar Energy in India. In: Low Carbon Energy Supply. Green Energy and Technology Series. Springer. The chapter "Perspective of Solar Energy in India" by Atul Sharma, Amritanshu Shukla, and Karunesh Kant (2018) [11] provides a comprehensive and policy-oriented overview of India's solar energy sector, situating solar power as a central pillar in the country's transition toward a low-carbon and energy-secure future. Written at a time when India's renewable energy ambitions were rapidly expanding, the chapter effectively captures the strategic importance of solar energy in addressing chronic energy shortages, reducing dependence on fossil fuels, and mitigating environmental degradation.

A key strength of the chapter lies in its systematic assessment of solar resource availability and technological pathways in India. The authors clearly outline the country's vast solar potential, driven by favourable geographic and climatic conditions, and emphasize that solar energy can contribute not only to capacity addition but also to long-term energy security. The discussion on both solar photovoltaic (PV) and solar thermal (concentrating solar power—CSP) technologies adds depth to the analysis, highlighting CSP as an emerging and underutilized option with significant future potential for grid-scale electricity generation.

The chapter offers a well-structured review of policy frameworks and promotional mechanisms supporting solar energy deployment in India. Initiatives such as national missions, incentive schemes, and regulatory reforms are discussed as critical enablers of solar growth. By linking policy support with market development, the authors demonstrate how solar energy has evolved from a niche technology into a mainstream component of India's energy mix. This policy-focused approach enhances the relevance of the chapter for planners, administrators, and energy analysts.

Another important contribution of the chapter is its balanced treatment of achievements and constraints. While acknowledging India's rapid progress in solar capacity addition, the authors critically examine persistent barriers such as high initial investment costs, land availability, grid integration challenges, and technological limitations. This realistic appraisal strengthens the analytical credibility of the chapter and underscores the need for sustained policy support, innovation, and institutional coordination.

From a future-oriented perspective, the chapter articulates a clear roadmap for expanding solar energy in India, emphasizing research and development, improved efficiency, and diversification of applications. The identification of solar thermal technologies as a promising avenue is particularly noteworthy, as it broadens the solar discourse beyond PV-dominated narratives and aligns with the requirements of industrial and utility-scale applications.

Largely, Sharma *et al*. (2018) [11] present a concise yet insightful synthesis of India's solar energy landscape, effectively bridging technology, policy, and sustainability concerns. Although the chapter does not delve into region-specific contexts such as high-altitude or cold-arid areas, its national-level analysis provides a strong conceptual foundation for understanding solar energy's role in India's low-carbon transition. The chapter remains a valuable reference for researchers, policymakers, and students seeking to understand the opportunities, challenges, and future directions of solar energy development in India.

Rajshree, B., & Manan, S. (2021) [9]. Solar photovoltaic energy in India: Business feasibility study and analogy of policies. International Journal of Energy and Water Resources, 5, 133–144. The article by Rajshree and Manan (2021) [9] provides a systematic and business-oriented assessment of the solar photovoltaic (PV) sector in India, focusing on its economic feasibility, prevailing business models, and supportive policy environment. Set against the backdrop of India's rapidly growing electricity demand and the imperative to reduce dependence on fossil fuels, the paper convincingly establishes solar PV as a technically mature and economically competitive energy source, particularly after achieving grid parity.

A major contribution of the study lies in its explicit focus on business feasibility, an aspect often underrepresented in technically driven renewable energy literature. Through an extensive literature review, the authors examine how strategic business models can enable effective scaling of solar PV deployment in India. The discussion of engineering, procurement, and construction (EPC) models, along with the role of solar equipment manufacturers, provides practical insight into the structure and functioning of India's solar industry. This perspective is especially valuable for investors, entrepreneurs, and policymakers seeking to understand the commercial dynamics of renewable energy markets.

The paper also offers a concise yet informative review of India's solar energy policies, highlighting the government's proactive role in creating a favorable ecosystem for PV adoption. Policy instruments such as financial incentives, regulatory support, and national renewable energy missions are discussed as key drivers that have facilitated market confidence and accelerated solar installations. By linking policy frameworks with business viability, the study underscores the importance of regulatory stability and long-term planning in attracting private investment.

Strength of the article is its balanced treatment of opportunities and challenges. While emphasizing the

immense potential of solar PV in a tropical country like India, the authors critically identify persistent barriers, including technological limitations, infrastructure constraints, political uncertainties, and financial risks. The discussion on mitigation measures—such as improved financing mechanisms, policy consistency, and technological innovation—adds analytical depth and reinforces the practical relevance of the study.

From a sustainability perspective, the article implicitly aligns solar PV deployment with broader goals of energy security, environmental protection, and economic development. Although the study remains largely national in scale and does not explore region-specific contexts, its findings are applicable to diverse regions across India, including emerging and remote solar markets. The achievement of grid parity, as highlighted in the paper, is particularly significant as it marks a turning point where solar energy transitions from being policy-driven to market-driven.

To put it briefly, Rajshree and Manan (2021) [9] present a well-structured and policy-relevant analysis that bridges the gap between renewable energy economics and governance. The article serves as a valuable reference for understanding the commercial viability and policy support mechanisms of solar PV in India, and it offers important insights for researchers, policymakers, and industry stakeholders working toward a sustainable and economically resilient energy transition.

Environmental Change and Development in Ladakh, Indian Trans-Himalaya (2023) Edited by Blaise Humbert-Droz, Juliane Dame, and Tashi Morup Series: Advances in Asian Human-Environmental Research Publisher: Springer Nature Switzerland. The edited volume Environmental Change and Development in Ladakh, Indian Trans-Himalaya (2023) provides a comprehensive, interdisciplinary, and empirically grounded examination of the profound transformations unfolding in Ladakh, a high-altitude trans-Himalayan region of strategic, ecological, and cultural significance. Bringing together sixteen chapters by scholars from diverse disciplines, the book critically explores how climate change, infrastructural expansion, geopolitical dynamics, tourism growth, and socio-economic transitions are reshaping Ladakh's environment and society. The volume stands out as one of the most authoritative and up-to-date academic contributions on Ladakh's contemporary challenges and development trajectories.

A major strength of the book lies in its integrated human–environment perspective. The chapters systematically document environmental changes such as glacier retreat, altered hydrological regimes, extreme weather events, and land-use transformations, while simultaneously analyzing their implications for livelihoods, mobility patterns, cultural identity, and governance structures. This dual focus allows the book to move beyond purely physical or social analyses and instead present Ladakh as a coupled socio-ecological system, where environmental stressors and development processes interact in complex and often uneven ways.

The volume is particularly effective in situating Ladakh's recent transformations within its geo-strategic and political context. The expansion of road networks, military infrastructure, and tourism-related development is critically examined not only as a driver of economic change but also as a source of ecological pressure and social reconfiguration. Several chapters highlight how increased connectivity with mainland India has accelerated modernization while simultaneously intensifying resource extraction, waste generation, and pressure on fragile mountain ecosystems. This nuanced analysis avoids simplistic narratives of development by foregrounding trade-offs, contradictions, and regional inequalities.

Another notable contribution of the book is its attention to local perspectives and community experiences. The editors and contributors emphasize how Ladakhi communities negotiate environmental change through adaptation strategies, cultural practices, and evolving identities. Issues of heritage, belonging, and socio-cultural continuity are carefully woven into discussions of development, ensuring that sustainability is treated not merely as a technical goal but as a socially embedded and culturally contingent process.

Importantly, the book does not limit itself to diagnosis alone. Several chapters engage with the future of Ladakh, identifying key environmental challenges likely to intensify in the 21st century, including water scarcity, climate-induced hazards, and governance constraints. The concluding sections offer critical reflections on pathways toward sustainable development, advocating for context-sensitive planning, ecological limits, and participatory governance. In doing so, the volume contributes meaningfully to broader debates on sustainability in high-mountain regions and climate-vulnerable peripheries.

From an academic standpoint, the book's interdisciplinary approach—drawing on geography, anthropology, environmental science, development studies, and political ecology—enhances its analytical depth and makes it valuable for a wide scholarly audience. While the diversity of chapters occasionally leads to variations in methodological depth, this is a common feature of edited volumes and does not detract from the overall coherence and significance of the work.

So, Environmental Change and Development in Ladakh, Indian Trans-Himalaya is a seminal and timely contribution to Himalayan studies and human–environment research. It provides critical insights into how global processes such as climate change and development intersect with local realities in Ladakh, and it offers informed perspectives for steering the region toward ecologically sensitive and socially just development pathways. The book is an essential reference for researchers, policymakers, planners, and students concerned with environmental change, sustainable development, and high-mountain regions.

Raghuwanshi, S. S., & Arya, R. (2019) [8]. Renewable energy potential in India and future agenda of research. International Journal of Sustainable Engineering, 12(5), 291–302. The paper by Raghuwanshi and Arya (2019) [8] offers a comprehensive, data-rich, and policy-relevant review of India's renewable energy landscape, systematically assessing the potential, regional distribution, and growth trajectory of major renewable energy resources, including solar, wind, small hydropower, biomass, geothermal, and tidal energy. Published in the International Journal of Sustainable Engineering, the study is particularly valuable for its integrated national perspective, combining statistical evidence, government data, and an explicit research agenda aimed at strengthening India's transition toward sustainable energy systems.

A major strength of the paper lies in its robust methodological framework, which draws extensively on

secondary data from authoritative sources such as the Ministry of New and Renewable Energy (MNRE), Central Electricity Authority (CEA), TERI, and international agencies. The authors clearly outline their multi-step methodology—data compilation, capacity assessment, literature review, and identification of research gaps—allowing transparency and reproducibility. This structured approach enables the paper to move beyond descriptive statistics and provide analytical insights into spatial and sectoral disparities in renewable energy deployment across India.

The paper provides an in-depth assessment of solar energy potential, highlighting India's vast annual solar availability (approximately 5000 trillion kWh/year) and the rapid growth following the Jawaharlal Nehru National Solar Mission (JNNSM). Using state-wise and region-wise data (Tables and Figures on pages 4–6), the authors demonstrate that western and southern states—such as Rajasthan, Gujarat, Tamil Nadu, Maharashtra, and Madhya Pradesh—dominate installed solar capacity due to high irradiance levels, land availability, and better grid infrastructure. At the same time, the study critically notes the underperformance of Himalayan and northeastern states, attributing it to financial, technical, and institutional constraints. This spatial analysis is particularly relevant for understanding renewable energy planning in mountain regions like Ladakh, where high resource potential contrasts sharply with low installed capacity.

Beyond solar energy, the paper offers a balanced evaluation of other renewable sources. Wind energy is identified as the largest contributor to India's renewable installed capacity (over 56% as of 2016–17), with Tamil Nadu, Maharashtra, Gujarat, and Rajasthan leading deployment. The discussion on small hydropower (SHP) is notable for its emphasis on Himalayan regions, recognizing both their high potential and the associated environmental and safety challenges. The sections on biomass and geothermal energy further broaden the paper's scope, underscoring their importance for rural and decentralized energy systems, particularly in states like Jammu & Kashmir and other agrarian regions.

One of the most significant contributions of the paper is its forward-looking research agenda. Rather than limiting itself to resource assessment, the study identifies critical gaps in renewable energy research, particularly in system reliability, performance optimization, and hybrid renewable systems. The authors strongly advocate for reliability assessment using indices such as Loss of Load Probability (LOLP) and propose optimization of solar and hybrid systems (including diesel–renewable combinations) as priority research areas. This emphasis on reliability is especially relevant for remote and climatically extreme regions, where uninterrupted power supply is crucial for livelihoods and infrastructure.

From a sustainability perspective, the paper convincingly links renewable energy expansion with environmental protection, energy security, and socio-economic development. The authors highlight the adverse impacts of fossil fuel dependence—such as greenhouse gas emissions, pollution, and import dependency—and position renewable energy as a strategic solution for India's long-term development goals. The discussion of India's ambitious target of 175 GW of renewable energy capacity by 2022 provides important policy context and underscores the scale of transformation envisioned by national planners.

While the paper excels in breadth and national-scale analysis, it remains largely macro-level and does not deeply explore local governance, social acceptance, or region-specific adaptation challenges. Nevertheless, this limitation is inherent to its objective as a national review and does not diminish its value as a foundational reference.

Hence, Raghuwanshi and Arya (2019) [8] present a thorough, well-documented, and analytically sound review of India's renewable energy potential and future research priorities. The paper is particularly useful for researchers, policymakers, and planners seeking a holistic understanding of India's renewable energy resources, regional disparities, and the technical–institutional challenges that must be addressed to achieve a sustainable and reliable energy transition.

Conclusion

This review paper on solar energy reveals Ladakh's solar-led transition as viable yet challenged, balancing abundant resources with extreme conditions through innovations like decentralized systems, cogeneration, and floating Photo-Voltaic. While technical maturity and national policies enable progress, governance tensions extractivism vs. autonomy demand participatory, pluriversal tactics integrating civic control, flexibility approaches, and TERI's low-carbon scenarios. Future research should prioritize equitable frameworks, field pilots and techno-economic modeling to realize climate-resilient, carbon-neutral futures in fragile Himalayan ecosystems.

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