Solar Energy as a Pathway to a Sustainable and Equitable Future: A Case Study of Uttarakhand

[1]Sulakshna Sharma
Research Scholar
Department of Political Science
HNB Garhwal University (A Central University)
Srinagar Garhwal, Uttarakhand-246174

[2]Dr. Narinder Singh
Assistant Professor
Department of Sociology and Social Work
HNB Garhwal University (A Central University)
Srinagar Garhwal, Uttarakhand-246174

ABSTRACT

The global shift toward renewable energy has become important for promoting sustainability and reducing climate change, especially in environmentally sensitive and remote regions. This study explores the role of solar energy in supporting sustainable and equitable development in the Himalayan state of Uttarakhand, India. Although the state has strong solar potential, many remote mountain villages still face challenges related to electricity access, environmental concerns, and uneven regional development. The study uses a qualitative research approach based on secondary data to examine policy frameworks, institutional arrangements, and decentralised solar initiatives in the state. The findings suggest that decentralised solar systems—such as rooftop installations, solar micro-grids, and small photovoltaic plants—can improve electricity access in remote areas, create local employment opportunities, and reduce environmental pressures associated with large hydropower projects. The study also highlights the important role of state agencies such as the Uttarakhand Renewable Energy Development Agency (UREDA) and Uttarakhand Power Corporation Limited (UPCL) in promoting solar energy development. However, several challenges continue to limit wider adoption, including delays in government procedures, financial constraints, and regulatory issues.

Keywords

Solar energy, Sustainable development, Decentralised energy systems, Rural energy access and Himalayan region.

This quote means that solar energy represents more than just electricity generation. When Narendra Modi says it is a "symbol," he suggests that adopting solar power shows a nation's dedication to clean energy, environmental protection, and long-term development. In simple terms, solar energy reflects our responsibility and commitment to building a greener and more sustainable future.

Introduction

The Sun's radiation is a source of solar energy. Solar energy is transformed into electricity using photovoltaic panels and solar thermal panels (IEA, 2022). As a renewable, non-polluting energy source, it provides an important alternative to fossil fuels and supports efforts to reduce carbon emissions and promote low-carbon development (IPCC, 2022). However, a pathway refers to a long-term process that supports changes at the levels of society, technology and energy system (Geels, 2002). Therefore, solar energy should not be seen only as a technology for generating electricity, but also as means of supporting wider development goals. A sustainable future refers to long-term development that balances environmental protection, economic growth, and social well-being without overusing natural resources (WCED, 1987).

Solar energy is very helpful in promoting sustainability by mitigating greenhouse gas emissions in turn, it reduces environmental damage and enhances energy security at the same time (IRENA, 2021). At the same time, the idea of an equitable future highlights fairness in access to energy resources and opportunities, ensuring that remote and disadvantaged communities have affordable, reliable electricity (UNDP, 2021).

In recent years, solar energy has become an important part of renewable energy development in Uttarakhand, mainly because the state receives strong sunlight and increasing policy support from the government. The Himalayan state receives around 4.5–5.5 kWh of solar radiation per square meter per day and experiences nearly 300 sunny days each year, making it suitable for solar photovoltaic power generation (MNRE, 2023; UREDA, 2022).

Despite its mountainous terrain and limited flat land, the state has steadily increased its solar capacity over the past decade. The amount of solar power increased significantly from about 5 MW in 2014-15 to almost 320 MW by 2020. This happened largely due to government programmes such as rooftop solar and decentralised solar setups (Central Electricity Authority [CEA], 2021). Projections indicate that the installed capacity will attain approximately 575 MWs by the fiscal year 2023-2024 and is anticipated to surpass 1 GW of solar energy by 2026. This accomplishment constitutes a significant benchmark within the renewable energy sector (CEA, 2024; Economic Times Energy, 2026).

Uttarakhand, a Himalayan state in northern India, is known for its fragile ecology, mountainous landscape, and scattered rural settlements. Due to its unique geographical and environmental conditions, the state offers a crucial case study for understanding how decentralised solar energy initiatives can foster both sustainability and inclusive regional development (Government of Uttarakhand, 2020; MNRE, 2022). The global transition to renewable energy is central to discussions on sustainable development, particularly in ecologically sensitive and socio-economically diverse areas (IPCC, 2022; UNDP, 2021).

In this regard, Uttarakhand presents a distinctive scenario characterised by co-existing environmental risks, challenging terrain and unequal development patterns (Government of Uttarakhand, 2020). Historically, the state has dependent significantly on hydropower and forest resources for its progress. Neverthless, it faces now multiple challenges, which include restricted electricity access in remote villages, rural out-migration, and environmental deterioration (Planning Commission of India, 2013; Sharma, 2019).

In such conditions, solar energy offers a promising pathway toward a more sustainable and equitable future. Leveraging ample sunlight and enhanced governmental support through initiatives such as the National Solar Mission, decentralised solar systems possess the capacity to advance rural electrification, mitigate carbon emissions and generate novel livelihood opportunities (IRENA, 2021; MNRE, 2022).

In addition, community-based and rooftop solar projects can help expand energy access while reducing the environmental risks associated with large infrastructure projects (Sovacool, 2017). This study, therefore, examines how solar energy development in Uttarakhand can contribute not only to environmental sustainability but also to social justice, balanced regional development, and inclusive growth.

Literature Review

Recent studies show that solar energy is not only a clean and low-carbon technology but also an important tool for improving energy access, protecting the environment, and supporting regional development (Geels, 2002; IPCC, 2022). This perspective is especially relevant in the case of Uttarakhand, where mountainous terrain, scattered villages, and ecological sensitivity make conventional energy systems difficult to expand. Research on solar potential indicates that hilly regions like Uttarakhand still have significant capacity for rooftop and small-scale solar power generation**,** despite geographical constraints (Sharma & Goel, 2017). Studies using spatial mapping and modelling further show that solar photovoltaic (PV) and solar-thermal technologies can be successfully implemented across different districts. Even with seasonal variations, large-scale rooftop installations could make an important contribution to meeting local electricity demand (IRENA, 2021; IEA, 2022).

Policy studies also highlight the growing institutional support for solar energy in the state. Initiatives such as the Uttarakhand Solar Policy (2023) and national renewable energy programmes implemented by the Ministry of New and Renewable Energy (MNRE) encourage decentralised solar systems, including rooftop and community-based solar projects (MNRE, 2022). However, some studies point out a policy challenge. In many cases, it is cheaper for the state to purchase solar power from large projects located in other states. This creates a tension between promoting local solar projects and relying on cheaper external sources, which highlights the need for better coordination, simpler approval processes, and improved financing mechanisms (Sovacool, 2017).

A large body of research supports the use of decentralised solar systems, such as mini-grids, rooftop solar panels, and stand-alone solar units, especially in mountainous and remote areas. These systems can

provide reliable electricity to households, schools, and health centres while reducing the environmental risks associated with large infrastructure projects (Bhattacharyya, 2012).

At the same time, studies on energy justice warn that the benefits of renewable energy transitions may not be distributed equally. Without targeted subsidies, community ownership models, and livelihood-based applications—such as agro-processing or tourism services—some communities may not fully benefit from solar energy programmes (Sovacool & Dworkin, 2015; UNDP, 2021). Researchers also emphasise the importance of gender-sensitive approaches, noting that women's economic participation and the time saved through improved energy access are important but often overlooked outcomes.

Environmental studies often compare solar energy with hydropower development in Himalayan regions. In Uttarakhand, large hydropower projects have been linked with problems such as forest diversion, landscape instability, and damage to local ecosystems (Government of India, 2013). Although solar energy projects can also raise concerns related to land use and the visual impact of large ground-mounted installations, research shows that solar power produces far fewer greenhouse gas emissions and causes less environmental disturbance compared to conventional energy sources (IPCC, 2022; IRENA, 2021). Because of this, many scholars suggest prioritising rooftop solar systems and installing solar plants on degraded or unused land to reduce environmental impacts.

Despite these benefits, several challenges still affect the implementation of solar energy projects. Studies point to issues such as complex land and forest clearance procedures, limited grid infrastructure, lack of financing for small entrepreneurs, delays in supply chains, and administrative hurdles related to approvals and power purchase agreements (MNRE, 2022).

At the same time, some state-level initiatives—such as the expansion of rooftop solar systems and the Mukhyamantri Saur Swarojgar Yojana—have shown positive results. These programmes have helped reduce electricity costs for households and created employment opportunities in districts like Dehradun and Haridwar. However, achieving the state's ambitious solar energy targets by 2027 will require stronger institutional coordination, environmental safeguards, and capacity-building efforts (Government of Uttarakhand, 2023).

Overall, existing studies suggest that solar energy has the potential to support both environmental sustainability and socio-economic development in Uttarakhand. However, this will depend on effective governance, better financing options, and careful consideration of ecological conditions while planning and implementing solar projects.

Sustainability Transition Theory, particularly the Multi-Level Perspective (MLP) developed by Geels (2002), helps explain how changes in energy systems take place. According to this theory, energy transitions occur through interactions between three levels: niches, regimes, and the broader landscape. In Uttarakhand, decentralised solar initiatives—such as rooftop systems and community-based solar micro-grids—can be

seen as niche innovations that challenge the existing energy system. Traditionally, the state's energy system has been dominated by centralised hydropower generation and grid-based electricity distribution. At the broader level, pressures such as climate change commitments, disaster risks in the Himalayan region, and national renewable energy targets set by the Ministry of New and Renewable Energy are also encouraging a transition toward cleaner energy sources.

From the perspective of the Multi-Level Perspective (MLP), the Uttarakhand Solar Policy (2023) can be understood as a policy response at the regime level that supports the growth of new solar innovations. The policy encourages the adoption of solar energy through subsidies, regulatory reforms, and incentives for decentralised solar projects. However, existing studies suggest that several institutional challenges can slow this transition. These include bureaucratic delays, complicated forest clearance procedures, and the tendency to purchase cheaper solar power from other states instead of promoting local projects. Therefore, the success of the renewable energy transition in Uttarakhand depends on better coordination between local solar initiatives, supportive government policies, and broader pressures such as climate change concerns and the need to reduce carbon emissions (IPCC, 2022).

In addition to this perspective, the Energy Justice framework (Sovacool & Dworkin, 2015) provides another useful way to understand renewable energy transitions. This framework focuses on three main principles: distributional justice, procedural justice, and recognition justice**.** Distributional justice looks at how the benefits of solar energy are shared. In Uttarakhand, wealthier households may find it easier to install rooftop solar systems, while poorer communities may struggle to access these technologies unless special subsidies or community ownership models are provided. Procedural justice focuses on fair and inclusive decision-making, ensuring that rural communities, women's self-help groups, and other marginalised groups are involved in planning and implementing solar projects. Recognition justice highlights the importance of acknowledging the specific challenges faced by remote hill communities, such as energy poverty, climate risks, and migration pressures.

Research Gap

Although many studies discuss solar energy and highlight its environmental and socio-economic benefits, several important gaps still remain in the context of Uttarakhand. First, there is limited research that examines the actual socio-economic impacts of solar projects at the household and community levels, especially in remote hill districts. Second, only a few studies analyse the institutional relationship between new solar initiatives at the community level and existing energy institutions such as state utilities and regulatory bodies using the framework of Sustainability Transition Theory. Third, the role of public participation in the planning and implementation of solar projects has not been studied in sufficient detail.

Statement of the Problem

Uttarakhand is a Himalayan state known for its fragile environment, mountainous terrain, scattered villages, and uneven regional development. Because of these conditions, the state continues to face several challenges related to energy access, environmental degradation, and socio-economic vulnerability. Although Uttarakhand has significant solar potential and supportive government policies, the role of solar energy in achieving both environmental sustainability and social equity has not yet been fully examined.

The state has traditionally depended on hydropower and centralised electricity systems. However, administrative delays, financial limitations, and environmental concerns in fragile mountain ecosystems raise important questions about how effective and inclusive the solar transition can be. Therefore, it is important to understand the institutional, environmental, and socio-economic conditions required to support a fair and sustainable energy transition in Uttarakhand.

Research Objectives

1. To examine the role of decentralised solar energy systems in promoting sustainable and equitable development in Uttarakhand.
2. To analyse the role of nodal agencies like UREDA and UPCL in the implementation and decentralisation of solar energy in the state.

Research Methodology

This study uses a **qualitative and descriptive research design** based mainly on the analysis of secondary data. It examines how decentralised solar energy contributes to sustainable and equitable development in Uttarakhand by reviewing policy documents, institutional frameworks, and existing research studies. This approach helps to understand the effectiveness of solar initiatives in the state without conducting primary field surveys.

The study relies on secondary data collected from several reliable sources. These include the Uttarakhand Solar Policy (2023)**,** earlier renewable energy policies such as the Solar Policies of 2013 and 2018, reports from the Ministry of New and Renewable Energy (MNRE), and publications from the Uttarakhand Renewable Energy Development Agency (UREDA). In addition, the research also uses information from peer-reviewed journal articles, books, and research reports**.**

The study also includes a comparative analysis of Uttarakhand's decentralised solar initiatives with similar programmes in other Indian states. This comparison helps identify useful policy lessons, best practices, and gaps that may influence the future development of solar energy in Uttarakhand.

DISCUSSION

Solar energy development in Uttarakhand has largely focused on distributed and decentralised systems**,** such as rooftop solar installations, solar pumps, micro-grids, and small-scale photovoltaic plants. These initiatives are particularly important in remote hill districts where extending conventional grid connectivity is difficult. In mountainous regions like Uttarakhand, decentralised solar systems have gradually become an important

tool for supporting both sustainable development and social inclusion.The state's rugged terrain, scattered villages, and limited infrastructure make the expansion of traditional grid-based electricity networks both technically complex and financially expensive. As a result, decentralised solar technologies—such as rooftop panels, solar home systems, micro-grids, and solar-powered irrigation pumps—are increasingly seen as practical alternatives for improving electricity access in rural and remote communities. By generating power close to where it is consumed, these systems help reduce transmission losses and provide a more reliable source of energy for geographically isolated settlements (Bhattacharyya, 2015; Ministry of New and Renewable Energy [MNRE], 2023).

As a result, decentralised solar energy not only helps diversify the state's energy sources but also supports environmental sustainability and more inclusive regional development (Sovacool, 2012). In Uttarakhand, several decentralised solar initiatives have been introduced to promote renewable energy and local employment. One important example is the Mukhyamantri Solar Self-Employment Scheme (MSSY). This program encourages individuals and small entrepreneurs to set up solar photovoltaic plants with capacities between 20 kW and 200 kW**.** These plants generate electricity while also creating employment opportunities at the local level.

Under the scheme, local residents are able to produce solar power and sell it to the state electricity distribution company. This provides an additional source of income and helps strengthen rural livelihoods in many parts of the state (Uttarakhand Renewable Energy Development Agency [UREDA], 2023).

Such initiatives show how decentralised renewable energy systems can support socio-economic development by involving local communities in the renewable energy sector (Sovacool, 2012). When local people participate in producing solar power, they not only gain new income opportunities but also become active contributors to the clean energy transition. In this way, decentralised solar energy can promote economic growth, environmental protection, and social equity at the same time (United Nations, 2015).

Decentralised solar energy systems also play an important role in protecting the environment. By generating electricity from sunlight, these systems reduce dependence on fossil fuels and help lower carbon emissions. They can also decrease the heavy reliance on large hydropower projects for electricity generation. Compared to large infrastructure projects, solar energy has fewer environmental impacts and helps avoid problems such as deforestation and disruption of river ecosystems (MNRE, 2023). In addition, small-scale solar installations require less land and infrastructure, which helps protect the fragile landscapes of the Himalayan region (Bhattacharyya, 2015). Therefore, decentralised solar energy supports low-carbon development and helps build climate-resilient energy systems (International Energy Agency [IEA], 2022).

Another important aspect of decentralised solar energy in Uttarakhand is its ability to encourage community participation and strengthen local governance in energy management**.** These systems allow local communities, small entrepreneurs, and cooperative groups to take a more active role in producing and managing electricity. This involvement increases a sense of local ownership and also raises awareness about

sustainable energy practices. In many rural areas, solar energy programs have been implemented with the support of self-help groups, village institutions, and local governance bodies (UREDA, 2023).

Such participatory approaches are especially important in mountainous regions, where local knowledge and community involvement often determine the success of development projects (Bhattacharyya, 2015).

Decentralised solar systems also help address regional inequalities in electricity access within Uttarakhand. Many hill districts, including Uttarkashi, Chamoli, and Pithoragarh**,** frequently experience power shortages and weak grid connectivity because of difficult terrain and scattered settlements. In these areas, solar micro-grids and solar home systems have been introduced to provide reliable electricity for households, schools, health centres, and small businesses (MNRE, 2023; UREDA, 2022).

Better access to electricity improves people's quality of life. It supports important services such as education, healthcare, and communication, while also encouraging local economic activities like small businesses and agro-processing units (Bhattacharyya, 2015). In this way, decentralised solar energy helps reduce regional inequalities by ensuring that remote and marginalised communities also benefit from modern energy services (Sovacool, 2012).

Districts such as Tehri Garhwal, Uttarkashi, Dehradun, Haridwar, and Udham Singh Nagar have become important centres for solar energy projects because they have relatively better land availability and supporting infrastructure (Renewable Watch, 2024). To encourage further growth of solar energy, the Uttarakhand Solar Energy Policy 2023 has set a target of achieving 2,500 MW of solar power capacity by 2027. The policy focuses on expanding rooftop solar installations, solar systems on institutions, and larger solar power projects (Government of Uttarakhand, 2023).

The policy also promotes new approaches to overcome geographical challenges in the mountainous state. These include installing solar plants along canal banks and using government land for solar projects. Although Uttarakhand has traditionally depended on hydropower for electricity generation, solar energy is now emerging as an important complementary and sustainable alternative. It can help diversify the state's energy sources and improve long-term energy security (MNRE, 2023).

A district-level analysis of solar energy development in Uttarakhand shows that solar installations—such as rooftop systems, solar pumps, and decentralised photovoltaic plants—are unevenly distributed across the state's thirteen districts. This pattern largely depends on geographical conditions, infrastructure availability, and government policy initiatives. In the Garhwal Himalayan districts, solar energy development mainly takes the form of decentralised systems. For example, Tehri Garhwal has emerged as one of the leading districts under the Mukhyamantri Solar Self-Employment Scheme (MSSY). More than 300 solar projects have been approved in the district, and many small solar plants with capacities between 20 kW and 200 kW have been installed by local entrepreneurs (Uttarakhand Renewable Energy Development Agency [UREDA], 2023; Renewable Watch, 2024).

Under this scheme, local residents can generate solar power and sell it to the state electricity distribution company. This provides an additional source of income and helps improve rural livelihoods (Uttarakhand Renewable Energy Development Agency [UREDA], 2023). Such initiatives show how decentralised renewable energy systems can support local economic development by involving communities directly in the renewable energy sector (Sovacool, 2012).

This approach also reflects the broader goals of sustainable development, which focus on economic growth, environmental protection, and social equity (United Nations, 2015). Therefore, decentralised solar projects not only help produce clean electricity but also create employment opportunities and support local economic activities in hill regions (UREDA, 2023).

Similarly, districts such as Uttarkashi have seen a growing number of solar micro-grids and solar home systems, especially in high-altitude villages where the electricity grid is often unreliable. In Chamoli and Rudraprayag, solar street lights and off-grid photovoltaic systems have been installed as part of rural electrification programmes supported by the Ministry of New and Renewable Energy (MNRE, 2023). Many hill districts, including Uttarkashi**,** Chamoli, and Pithoragarh, frequently experience power shortages because of difficult terrain and scattered settlements. In such areas, solar micro-grids and solar home systems have been introduced to provide reliable electricity for households, schools, health centres, and small businesses (MNRE, 2023; UREDA, 2022).

In Pauri Garhwal, solar energy development is mainly seen in the form of household rooftop systems and small solar installations in institutions. This pattern reflects the district's scattered settlement structure and the limited availability of large flat land areas suitable for large-scale solar plants (UREDA, 2022).

In contrast, the plains and foothill districts of Uttarakhand have greater potential for grid-connected solar power because the terrain is relatively flat and the electricity network is better developed. Dehradun**,** the state's administrative capital, has become an important centre for rooftop solar installations. Many government offices, universities, hospitals, and residential buildings have adopted rooftop solar systems under national solar programs. Government reports indicate that Dehradun accounts for a large share of rooftop solar installations in the state and has also hosted several pilot solar projects implemented by state agencies (MNRE, 2023; Central Electricity Authority [CEA], 2024).

The industrial districts of Haridwar and Udham Singh Nagar have also seen significant growth in solar energy adoption. In these districts, many manufacturing units, commercial establishments, and agro-processing industries have installed rooftop solar systems. The availability of larger land areas in these regions has also made it possible to develop medium-scale solar photovoltaic plants connected to the electricity grid (CEA, 2024).

In the Kumaon Himalayan region, districts such as Almora, Nainital, Bageshwar, Champawat, and Pithoragarh mainly rely on decentralised solar technologies. These include rooftop solar panels, solar water

pumps for agriculture, and small off-grid solar systems that support households and community institutions in rural areas (UREDA, 2022; MNRE, 2023).

Together, these district-level initiatives have contributed to the steady growth of solar energy in Uttarakhand. Over the past decade, the state's installed solar power capacity has increased rapidly and has recently crossed 1 GW (CEA, 2024; Renewable Watch, 2024).

By improving electricity access in remote areas, creating local employment opportunities, reducing environmental impacts, and encouraging community participation, decentralised solar systems support several aspects of sustainable development at the same time (Sovacool, 2012). As Uttarakhand continues to expand its renewable energy programs and implement supportive policies, decentralised solar energy is likely to play an increasingly important role in building a more inclusive and environmentally sustainable energy future for the Himalayan region (MNRE, 2023; UREDA, 2023).

The development and decentralisation of solar energy in Uttarakhand largely depend on the coordinated work of key state institutions, especially the Uttarakhand Renewable Energy Development Agency (UREDA) and the Uttarakhand Power Corporation Limited (UPCL)**.** These agencies play important roles in planning solar projects, implementing government policies, developing infrastructure, and integrating solar power into the state's electricity system. Their role is particularly important in a mountainous state like Uttarakhand, where scattered villages and difficult terrain make the expansion of the traditional electricity grid challenging.

UREDA functions as the main state agency responsible for promoting and implementing renewable energy programmes. It works closely with both central and state governments and serves as the implementing agency for several schemes supported by the Ministry of New and Renewable Energy (MNRE). UREDA's responsibilities include planning renewable energy projects, supporting the installation of new technologies, providing technical guidance, and spreading awareness about renewable energy among communities and institutions. The agency also manages various solar programmes such as rooftop solar installations, solar water heating systems, solar irrigation pumps, and decentralised solar electrification projects in rural areas (UREDA, 2026).

UREDA also focuses on promoting decentralised renewable energy systems that are well suited to the geographical conditions of Uttarakhand. Many villages in the state are located in remote mountainous areas where grid connectivity is limited or unreliable, making decentralised solar systems a practical solution. In addition, UREDA supports community-based and livelihood-oriented solar initiatives. For example, some programmes allow farmers and local landowners to install small solar power plants on their land and sell the electricity to the state grid through power purchase agreements**.**

Such initiatives not only increase renewable energy generation but also create additional income opportunities for rural communities. In one initiative, around 200 farmers from different districts were selected to install solar plants on their land**,** and the electricity generated was sold to the state government at fixed tariffs. This approach helps promote both decentralised energy production and rural entrepreneurship (Saur Energy, 2016).

In addition to UREDA, Uttarakhand Power Corporation Limited (UPCL) also plays an important role in the development of solar energy in the state. UPCL is responsible for supplying electricity to consumers and managing the distribution network across Uttarakhand. In the context of solar energy, UPCL helps connect solar power systems to the electricity grid and ensures that electricity generated from rooftop panels and solar plants can be supplied to the grid. The corporation also implements net-metering systems, which allow consumers to use solar energy more efficiently.

Under the Uttarakhand Solar Energy Policy 2023**,** UPCL works closely with UREDA to promote solar energy projects in the state. This includes encouraging rooftop solar installations and introducing group net-metering systems for government buildings and institutions. Net-metering and group net-metering are important mechanisms for promoting decentralised solar energy. Through these systems, households, schools, and government offices can generate solar electricity on their premises and send any surplus power back to the electricity grid. This makes solar energy more financially beneficial for consumers and encourages wider adoption (Government of Uttarakhand, 2023).

Another important responsibility of UREDA and UPCL is supporting the state's Renewable Purchase Obligation (RPO) framework. According to the regulations of the Uttarakhand Electricity Regulatory Commission (UERC)**,** electricity distribution companies such as UPCL must obtain a certain portion of their electricity from renewable energy sources. This policy encourages the integration of solar power into the state's electricity system and helps create steady demand for renewable energy projects (Government of Uttarakhand, 2019).

Overall, the coordinated efforts of UREDA and UPCL form the institutional foundation of solar energy development in Uttarakhand. By working together, these agencies support the expansion of decentralised solar systems that are suitable for the state's mountainous geography and scattered settlements. Their role is therefore essential for achieving Uttarakhand's renewable energy goals and promoting a more sustainable and inclusive energy transition. Experiences from other Indian states provide useful lessons for expanding solar energy in Uttarakhand. States such as Gujarat and Rajasthan have successfully increased their rooftop solar capacity through clear net-metering policies, simpler approval procedures, and financial incentives (MNRE, 2023). For example, Gujarat has become one of the leading states in rooftop solar adoption in India. The state now has more than 3 GW of installed rooftop solar capacity**,** largely supported by the SURYA-Gujarat programme, which encourages households to install solar panels through subsidies and government support (MNRE, 2023; Government of Gujarat, 2022).

Similarly, Rajasthan has developed both large-scale and decentralised solar infrastructure. The state's total solar power capacity has crossed 20 GW**,** making it one of the largest solar producers in India (Central Electricity Authority [CEA], 2023). The Rajasthan Renewable Energy Policy has promoted rooftop solar systems and private sector participation by offering financial incentives and simplifying grid connection procedures. Other states have also made significant progress. Karnataka has installed more than 9 GW of solar capacity, supported by solar parks, community solar projects, and rooftop installations in both urban and rural areas (MNRE, 2023).

In Delhi, the Solar Policy (2020) has encouraged rapid rooftop solar adoption through generation-based incentives and an easy online approval system, which has led to a steady increase in distributed solar installations (NITI Aayog, 2022). These examples show that strong institutional coordination, supportive policies, and accessible financial support can greatly accelerate the adoption of renewable energy. For Uttarakhand, these experiences suggest that improving administrative coordination, providing better financing opportunities for small producers, and linking renewable energy programmes with rural development initiatives could strengthen the state's solar transition (IRENA, 2021; MNRE, 2023).

In simple terms, adopting best practices such as simplified regulatory procedures, community-based solar programmes, and targeted subsidies for rural households could help expand decentralised solar energy in Uttarakhand.

The findings of this study suggest that decentralised solar initiatives have significant potential to improve electricity access in remote areas of the state. By expanding the availability of clean energy, these systems can also create livelihood opportunities and support local economic development in rural communities. From an environmental perspective, solar energy offers a cleaner alternative to conventional energy sources and helps reduce the environmental pressures associated with large hydropower projects in fragile Himalayan ecosystems.

The study suggests that renewable energy programmes can create employment opportunities, encourage entrepreneurship, and improve rural livelihoods. At the same time, several institutional and governance challenges still limit the wider expansion of decentralised solar energy in Uttarakhand. Issues such as administrative delays, complicated land and forest clearance procedures, limited financial support for small producers, and weak grid infrastructure in mountainous areas continue to act as major barriers. Without appropriate policy support, the benefits of solar energy may remain concentrated among relatively wealthier households, which raises concerns about fairness and energy justice.

Overall, decentralised solar energy has significant potential to support sustainable and inclusive development in Uttarakhand. By improving energy access, protecting the environment, and encouraging community participation, solar energy can play an important role in building a more balanced and sustainable future for the state.

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