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Solar Energy, Pollution Mitigation, and Sustainable Development in Uttarakhand: A Region-Specific Assessment for a Climate-Vulnerable Himalayan State

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Abstract: Uttarakhand is in an acute development dilemma: how to fulfill a soaring demand of electricity without jeopardizing a delicate Himalayan ecosystem at risk of air pollution, seasonal forest fires, accelerated glacier melting, and the energy-access gap of remote hill communities. The utilization of solar photovoltaic (PV) technology has evolved from a conventional power-generating option to a comprehensive strategy for pollution mitigation, rural energy accessibility, and long-term climate resilience. The paper provides a geographically-oriented secondary-data evaluation of how solar PV growth can foster environmental development and sustainability in Uttarakhand. The official statistics, the policy documents at the national and state levels, the emission-factor data provided by the Central Electricity Authority (CEA), and the peer-reviewed literature on renewable energy, air quality, and the development of mountain regions are used to conduct the analysis. Findings show that solar energy is capable of significantly decreasing coal-related carbon emissions with current installed capacity (575.53 MW as of 2022-23) preventing about 0.66 million tons of CO_2 per year. The paper also assesses the role of solar energy in cleaner household energy transitions, energy security in terrain-fragmented districts, and rural livelihood diversification. The paper will offer a five-pillar Regional Clean Solar Transition Model to overcome these problems. The paper contends that sustainability outcomes and not megawatts alone should be used to measure the solar transition in Uttarakhand.

Keywords: Solar Energy • Uttarakhand • Air Pollution • Sustainability • Himalayan Region • Renewable Energy • Energy Access • Climate Resilience • Photovoltaics • Carbon Emissions

Introduction

Solar photovoltaic technology is among the most rapidly expanding sources of electricity in the world (IRENA, Renewable Power Generation Costs in 2023) due to the global call to decarbonize energy systems. By March 2024, installed solar capacity had passed 81.8 GW in India, which is backed by high national targets and falling module prices (Ministry of New and Renewable Energy (MNRE), Annual Report 2023–24) However, the translation of national ambition into the locally suitable deployment is not even and mountain states like Uttarakhand have issues that are not the same as the flat, sunlit plains on which most large-scale solar parks are located (Government of Uttarakhand Solar Energy Policy 2023). Uttarakhand is an ecologically important area in north India. But at the same time, the state is facing increased electricity demand due to urbanization and tourism, endemic energy poverty in remote hill regions, declining air quality, and increasing climate-induced cryosphere change (UPCL Dehradun, 2023), (India State of Forest Report 2021). These pressures are combined to ensure that energy planning has become a first-order sustainability issue. It has the potential to replace electricity which is tied to fossil fuels, decrease domestic reliance on biomass and kerosene, enhance grid reliability in terrain-divided districts, and offer a basis of local livelihood programmes (Department of Environment, Dehradun 2021).

In 2022-23, the installed solar capacity of the state was 575.53 MW and the Uttarakhand Solar Energy Policy 2023 targets 2,500 MW by 2028 (National Air Quality Status and Trends in India 2022). These numbers are an indication of a clear intent, yet the big question is whether this increase is being designed in a manner that actually would focus on pollution reduction and sustainability, or whether it is merely a replication of a generic capacity-expanding model that does not fit into the conditions of the Himalayas. The paper will respond to that question by means of a region-specific secondary-data evaluation. Rooftop-based growth in cities, mini-grid supply to rural hamlets, the strict environmental vetting of utility scale developments, and the incorporation of livelihood support into the solar policy are thus the way to go in order to attain sustainable results in this climate-endangered state. Fig. 1 depicts solar energy deployment and sustainability framework.

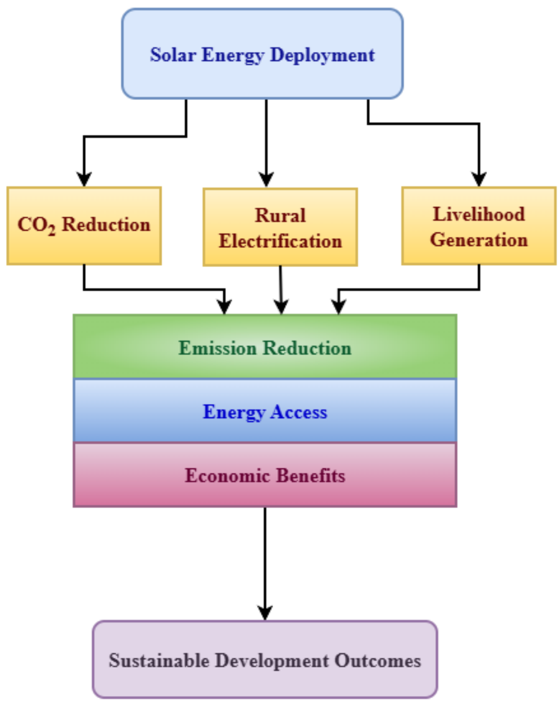

Fig. 1 Solar energy deployment and sustainability framework

Literature Review

The literature is consistent in its findings that the solar photovoltaic (PV) systems have significant environmental advantages in that they are able to decrease the reliance on electricity generated using fossil fuels. Solar PV also has a significantly reduced life-cycle carbon footprint compared to coal-fired power and helps to reduce emissions of CO_2, $PM_{2.5}$, SO_2, and NO_x (Hertwich et al 2015). It renders solar energy both significant in climate control and beneficial to air quality and human health in places where coal is still prevalent in the electricity grid (Buonocore et al. 2016). The solar energy has been growing faster in India as a part of national programs like the National Solar Mission and national renewable energy goals. Declining technology prices, favorable policy, and the growth of utility-scale systems and decentralized systems have reinforced the place of solar power in the national energy transformation (IRENA

2024; MNRE 2024). The current literature also reveals that the growth of renewables can play a significant role in minimizing the emission of carbon over the long term (IPCC 2022). Centralized electricity systems are not always effective in remoteness, fragmented settlements, difficult landscapes, and low grid reliability. Under these circumstances, the decentralized solar systems like mini-grids and stand-alone units have demonstrated high capabilities of enhancing access to energy, decreasing kerosene consumption, and promoting welfare at households (Ulsrud et al 2011). The success of these systems in the long run however relies greatly on maintenance arrangements, local technical capacity and sustainable financing (Denholm et al 2019). In a Himalayan and hill state setting, solar energy is also coming to be considered as a viable option to more ecologically invasive modes of energy generation. Research in Uttarakhand and other similar mountain areas has indicated that Solar mini-grids and local systems can enhance rural livelihood and minimize the household reliance on polluting fuels (Ulsrud et al 2011; Government of Uttarakhand 2023) Meanwhile, the utilization of biomass to prepare and heat food continues to be a significant contributor to indoor air pollution in hill communities (Andreae and Merlet 2001), which reinforces the argument of more efficient solar-based transitions in household energy (Smith et al 2014; Clean Cooking Alliance 2020). Agrivoltaics systems could contribute to the solution of the electricity generation vs. food production issue by co-locating solar panels with agricultural use on the same land. It seems that this approach would be relevant to mountain states like Uttarakhand, which have to be carefully tested in local ecological and farming conditions (Dupraz et al 2011).

Research Gap and Novel Contribution

The current studies on solar energy in India are inclined to work at the national level (Denholm et al 2019), Towards a Policy Framework, Government of India, New Delhi 2021) or concentrate on the engineering and economic optimization, as opposed to sustainability governance. At the state level, there have been studies of the energy sector in Uttarakhand which have covered hydropower or general renewable energy policy, but have not incorporated (a) quantified pollution-reduction potential (b) sustainability dimensions of remote communities (c) ecological risk factors dependent on the Himalayan landscape (d) a region-calibrated policy framework.

There are three key contributions of this paper. First, it introduces a systematic secondary-data estimate of the Uttarakhand current and projected solar power avoided emissions based on the CEA grid emission factor methodology, which allows to base the discussion on verifiable evidence. Second, it provides a multi-dimensional sustainability overview that connects the access to energy, livelihood creation, ecological risk, and resilience within a mountain-state setting. Third, it suggests a five-pillar Regional Clean Solar Transition Model as a viable policy framework that is consistent with the geography, development priorities and environmental constraints of Uttarakhand.

Methodology

The research is based on the secondary data using official statistics, policy documents, and published research (Google Scholar, Web of Science, and ScienceDirect, Quantitative Emission Estimation and Sustainability Framework Development). Remote hamlet and district-level solar performance data are limited. Consequently, the analysis lacks uniform precision at all the sub-state locations and the results must be viewed as region-level estimates and not very localized measurements.

Regional Context: Uttarakhand

Uttarakhand is a high ecologically important Himalayan state, possessing a wide coverage of forests, glacier-based river systems, and biodiversity protected areas. Meanwhile, it experiences increasing electricity demand, climate susceptibility, seasonal forest-fire pollution, and endemic energy issues in remote hill communities. Moderate to good solar potential exists in the state, especially in Districts of the plains and foothills, and capacity to harness solar power has been growing over the last few years. But the topography, the ecological tact and grid irregularity imply that solar development in Uttarakhand cannot be planned in the same way as traditional flat-land solar expansion models. The broader regional baseline is summarized in Table 1.

Table 1 Key Energy and Environmental Indicators for Uttarakhand

Indicator	Value
State area (km²)	53,483
Forest cover (% of state area)	~71%
Installed solar capacity (2022–23)	575.53 MW
Solar target (2028)	2,500 MW
Total electricity consumption (2021–22)	~14,500 Mus
GHI range (plains/foothills)	4.5–5.5 kWh/m²/day
Grid emission factor used (CEA)	0.727 tCO_2/MWh
Estimated current annual CO_2 avoidance	~0.66 Mt CO_2/year
Projected CO_2 avoidance at 2,500 MW	~2.87 Mt CO_2/year

Potential of Solar Plants in environmental pollution reduction

A. Carbon Emission Avoidance: Present and Future

With a CEA grid emission factor of 0.727 tCO_2/MWh (Intergovernmental Panel on Climate Change (IPCC), Shukla et al 2022), and an installed solar capacity of 575.53 MW (Ministry of Environment, Forest and Climate Change, Government of India, New Delhi, 2023) with a performance ratio of 0.80, and an estimated average of 4.5 hours of peak sun each day, annual electricity output is estimated to be about 756 million kWh (756 MUs). According to this estimation, the yearly emissions that are avoided are approximately 0.66 million tonne of CO_2 (Mt). The overall CO_2 emissions of the power-sector in India in 2022 were estimated at about 1,098 Mt indicating that the contribution made by solar to the state of Uttarakhand is significant. As summarized in Table 2, when the 2028 goal of 2,500 MW is met (Ulsrud et al 2011), the annual avoided emissions may rise significantly with the same operating conditions. This estimate is conditional depending on curtailment and grid integration.

Table 2 Estimated CO_2 Avoidance Under Capacity Scenarios

Scenario	Installed Capacity (MW)	Est. Annual Generation (MUs)	Avoided CO2 (Mt/year)
Current (2022–23)	575.53	~756	~0.66
50% of 2028 target	1,250	~1,642	~1.19
2028 target (2,500 MW)	2,500	~3,285	~2.39
Full 2028 target (high PR)	2,500	~3,942	~2.87

Note: Generation estimated using PR = 0.80, 4.5 peak sun hours/day; higher scenario uses PR = 0.86. Emission factor: 0.727 tCO_2/MWh (P. R. Shukla et al, 2022).

B. Decrease in Coal Reliance in the grid

Uttarakhand receives electricity imported in the national grid, which contained a coal portion of around 73 percent in 2022-23. Every step of local solar generation decreases the net grid draw and consequently the indirect coal burning that can be attributed to the consumption in the state. This decoupling of coal-fired power generation is crucial because it benefits climate-related reasons as well as due to the fact that it minimizes the fiscal and energy-security risks on the state due to volatility in coal-prices and grid-availability. The Uttarakhand Power Corporation Limited (UPCL) has already recognized the issue of intermittent supply in outlying hill districts; the local solar generation would offset these lapses to some extent (Ministry of Environment, Forest and Climate Change, Government of India, New Delhi, 2023).

C. Household Pollution Pathways

Without an effective grid electricity supply, the households in the regions tend to rely on kerosene lighting and biomass cooking and heating. The use of kerosene can produce high concentrations of PM 2.5, black carbon, and volatile organic compounds. The combustion of bio-mass is another significant cause of indoor air pollution and it is linked to chronic respiratory disease, especially in women.

Solar PV systems, in the form of home solar lighting systems, solar-powered electric cook stoves, or mini-grids supplied households, can lessen reliance on kerosene and aid in the uptake of better electric cooking devices. According to the Clean Cooking Alliance, the premature deaths caused by inaccessible clean-cooking in India may be avoided each year with universal access to clean-cooking in India. Although solar cannot and will not provide universal clean cooking in Uttarakhand, the effect of allowing electrification of cooking processes in remote communities is a clear and quantifiable form of pollution-reduction that is independent of the carbon arithmetic of grid electricity replacement.

D. Co-Benefits and Indirect Effects of Air Quality

The operation of solar PV plants does not create any stack emissions or any particulate matter, SO_2, or NO_8 (K. R. Smith, N. Bruce, K. Balakrishnan 2014). Solar growth indirectly helps improve the ambient air quality of areas downwind of thermal plants by decreasing the need of coal and diesel generation in the larger grid (India Energy Outlook 2021). Solar energy does not directly deal with forest-fire-induced pollution that is a common problem in Uttarakhand. Nevertheless, a consistent power supply to outlying forest-near communities would decrease the reliance on open fires as a source of heating and cooking, which could reduce the anthropogenic ignition risk factor that leads to some wildfire incidents. It is an immeasurable, mixed benefit that can be seen as an indirect way in which solar deployment contributes to air-quality enhancement, yet it is a reasonable secondary mechanism.

Implementation of electric vehicles (EV) within Uttarakhand, needs an efficient supply of clean electricity to fulfill its full potential in pollution reduction. With the local grid moving away coal in favor of solar generation, the effective emission factor of EV charging reduces, which reinforces the environmental argument of using electric mobility on the tourist routes and urban corridors of the state.

Sustainability Implications

A. Energy Security and Infrastructure Resilience

The topography of Uttarakhand is systemically weak in terms of infrastructure. Landslides, bridge failures, and excessive weather routinely affect the fuel supply chains and grid connectivity in the Garhwal and Kumaon hill districts. Decentralized solar generation base, especially when used in conjunction with battery storage, would decrease reliance on long and vulnerable transmission lines and central dispatch points. The Chamoli disaster of 2021, demonstrated the susceptibility of large water-dependent energy assets to hazards caused by

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climate (Department of Environment, Dehradun, 2021). The nature of small modular solar systems mounted on roofs and communal land is highly distributed and thus not prone to single-point failure. They are also useful in the reconstruction of energy after a disaster because of their quick deployment ability.

B. Rural Livelihoods and Employment

The Mukhyamantri Solar Swarojgar Yojana (Chief Ministers Solar Self-Employment Programme) is one of the most overt Indian efforts to relate solar installation to rural livelihood generation (Ulsrud et al 2011). In this programme, local farmers and youth are assisted to place small solar plants (25200 kW) on their agricultural or waste land with power purchase agreements offering them predictable revenues. This model has a dual role in meeting its two sustainability issues at once, namely increasing clean energy production and offering a new source of income that will decrease the migration pressure which has left many of the hill villages depopulated.

Solar implementation through training also creates local technical capacity to install, monitor and maintain-capacity that has long term economic value in a state whose energy sector is expanding.

C. Social Inclusion and Human Development

Modern educational and economic participation is a precondition to access to electricity. Solar electrification of schools prolongs productive study time, facilitates digital learning materials and promotes school-based health services. Solar power can have a significant positive impact on the quality of education in a state where most primary schools are geographically isolated without the extension of the grid. In the same manner solar-powered water pumping and purification can be used to enhance health conditions in villages.

Women and girls are the greatest beneficiaries of clean energy transitions that lead to lower biomass collection pressures and indoor pollution exposure. Direct gender equity implications of solar systems which shorten fuelwood collection time and enhance indoor air quality of homes can be seen in Uttarakhand, where male out-migration is high and women frequently control household energy by themselves.

D. Agrivoltaic Potential

One of the binding limitations to solar development in Uttarakhand middle and upper hills is land scarcity. Agrivoltaics systems, where solar panels and crops are placed on the same plot of land, provide a solution to producing electricity without transforming farmland to energy production. Studies carried out in the plains of India indicate that agrivoltaics systems with partial-shade settings can support crops such as wheat, pulses and some vegetables with minor changes in the yield. Agrivoltaics may be especially useful in the terraced agricultural environment of Uttarakhand.

E. Green Economy and Tourism Relations

The economy of Uttarakhand largely relies on tourism and religious, adventure and eco-tourism are all significant sources of revenues (UPCL, Dehradun, 2023). The lodges, heritage facilities and transportation corridors powered by solar energy can be part of a green tourism brand which will distinguish the state in an ever-sustainable market. Some operators of hill-tourism are already on voluntary solar switches and the state policy can institutionalize and speed up this move with green certification programs and subsidized financing (Ulsrud et al 2011).

Challenges, Risks, and Limitations

A. Topographic and Land Constraints

Topography is the most basic problem facing solar growth in Uttarakhand. The state is characterized by a very little flat land with approximately 93% of the state being hilly terrain. Large-scale solar parks need terrain that can be mounted and equipment access to install

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them and evenly irradiated. Any major deviation on the plains-only utility-scale development must be subject to ecological and geotechnical scrutiny. Fig. 2 highlights the main structural barriers to solar expansion in Uttarakhand, with terrain constraints, ecological sensitivity, grid limitations, seasonal variability, and financial barriers forming the core challenge set discussed in this section.

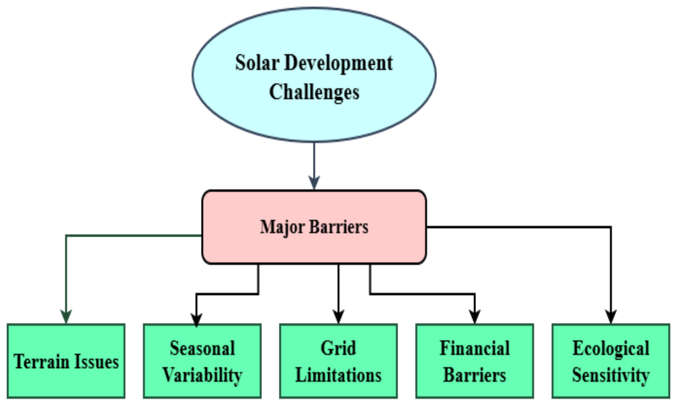

Fig. 2 Major barriers to solar development in Uttarakhand

B. Ecological Sensitivity and Biodiversity Risk

The high forest cover and protection in Uttarakhand also form no-go zones in terms of solar development creation and the formation of wide buffer zones in which siting is very sensitive. Legal limits on conversion of land-use are found in the Forest Conservation Act and Wildlife Protection Act, but enforcement standards depend on gaps in their implementation, and the quality of enforcement is vastly important. Solar installations that are not well located in ecologically sensitive places may interfere with wildlife patterns, increase soil erosion on the slopes, change the water drainage patterns, and cause land degradation which compromises the sustainability of the very landscapes that make the state so valuable.

C. Grid Integration and Storage Challenges

Variable solar generation presents grid stability technical challenges that are more severe in mountainous systems that have reduced redundancy. The swift cloud changes in the hilly regions may lead to fluctuation of voltages that put pressure on the distribution infrastructure. With a rise in solar penetration, the requirements of smart inverters, reactive power compensation, and storage integration are expanding. Historical data indicates that the distribution network in Uttarakhand that is controlled by the UPCL has experienced high aggregate technical and commercial (AT&C) losses and infrastructure ageing in the hill districts (Ministry of Environment, Forest and Climate Change, Government of India, New Delhi, 2023).

D. Seasonal Change and Snow Impact

The high-altitude areas of Uttarakhand are highly variable in terms of seasonal changes, unlike tropical areas where the sun irradiance is relatively constant. In winter cloud cover, snowfall on panels, and shorter day length reduce generation between November and February. Peak-season based system designs that do not consider winter troughs have in the past failed to deliver in Himalayan installations.

E. Remote District Financing Barriers

Remote hill districts have increased logistics, reduced project sizes, and increased maintenance uncertainty, which increase the perceived risk and consequently the cost of financing solar projects. Commercial banks and large developers of projects are structurally inclined towards large scale installations, located in plains. Solar will grow in the already-favored districts instead of minimizing geographic inequality because without specifically designed financial instruments, like blended finance facilities, risk-sharing guarantees, or state-backed concessional loans on hill-area projects, solar will concentrate in those areas.

F. End-of-Life and Waste Management

The useful life of solar PV panels is usually 25-30 years, at the end of which they enter the electronic waste stream, which includes potentially toxic elements like lead, cadmium, and selenium. The recycling facilities on solar panels in India are still in their infancy and mountain states have further transport cost issues of transporting end of life panels to recycling facilities. Otherwise, there is a risk that the existing generation of solar installations in Uttarakhand will result in a focused waste management issue in 2045-2055.

G. Implementation Governance

The quality of scheme implementation in remote locations has historically been skewed. Researchers recorded instances of technically competent solar installations which failed to operate within a few years because of poor maintenance plans, ownership ambiguity or lack of technical support (Ulsrud et al, 2011). The sustainability of solar implementation in Uttarakhand needs governance structures community participation, trained local technicians, proper accountability chains, and periodic third-party monitoring that transcend far beyond subsidies on installations.

Policy and Practical Recommendations

The regional analysis and the five pillars framework suggest the following recommendations. They are targeted to state energy planners, UPCL, UREDA (Uttarakhand Renewable Energy Development Agency) and counterparts at the central government.

R1. Rooftop Solar Acceleration: Uttarakhand ought to set out binding rooftop solar obligatory to new commercial establishments and institutional establishments in Haridwar, Dehradun and Udham Singh Nagar districts with a floor area exceeding certain floor area limit. It should be streamlined in registration of net-metering and have clear grievance procedures in order to mitigate resistance to adoption.

R2. Mini-Grid investment in Remote Hamlets: Solar mini-grids and hybrid (solar storage) installations need to be financed together by state and central government to the estimated 300-500 hamlets in Uttarakhand that lack access to a dependable grid connection (Ministry of Environment, Forest and Climate Change, Government of India, New Delhi, 2023). Maintenance and community operator training arrangements should also be funded and made part of project designs, which are not negotiable.

R3. Strict Ecological Suitable Testing: A solar project above 1 MW size is not to be approved without GIS-based ecological suitability testing that includes the forest proximity, slope gradient, status of a wildlife corridor, water bodies buffers, and soil stability. Projects greater than 5 MW should be subject to third-party review.

R4. Concessional Finance to Hill Districts: UREDA and financial institutions are recommended to develop a special hill-district solar finance window with reduced interest rates, flexible repayment and lower equity requirement of projects in the district with a high elevation of above 1000 m. Multilateral and national blended finance instruments should be considered.

R5. Solar-Livelihoods Integration: Mukhyamantri Solar Swarojgar Yojana needs to be improved with better off-take guarantee system, dispute resolution system and coordinated technical support to decrease the number of small solar entrepreneurs which are leaving their business (Ulsrud et al 2011).

R6. Clean energy-Air Quality Integration: The state is to develop a combined monitoring system that will be tied to solar deployment statistics with air-quality monitoring systems at

CPCB stations located within cities, which can allow assessing the contribution of solar expansion to the reduction of emissions to the environment with evidence.

R7. End-of-Life Planning: A decommissioning and waste management plan should be provided with every solar project that is granted permission in Uttarakhand as a condition of permission and the project must have a security deposit or an insurance instrument to comply upon decommissioning of the project.

The priorities are concisely summarized in Table 3, which illustrates the Regional Clean Solar Transition Model for Uttarakhand.

Table 3 Regional Clean Solar Transition Model for Uttarakhand

Pillar	**Strategy**	**Key Actions**	**Primary Beneficiaries**
1. Rooftop-First Urban Deployment	Prioritise low-conflict building-integrated solar in urban/peri-urban districts	Net-metering expansion; institutional rooftop mandates; simplified DISCOM approvals	Dehradun, Haridwar, Udham Singh Nagar
2. Remote Energy Justice via Mini-Grids	Serve isolated hamlets through solar mini-grids and hybrid systems	Targeted public investment; maintenance endowments; community-managed models	High-altitude Garhwal and Kumaon hamlets
3.Environment-Screened Utility Projects	Apply mandatory ecological suitability assessment before large-project approval	GIS-based land screening; biodiversity impact studies; slope and drainage analysis	All utility-scale project sites
4. Solar-Linked Livelihood Programmes	Integrate skill training, local ownership, and enterprise development with solar deployment	Swarojgar scheme expansion; certified technician training; cooperative ownership models	Rural youth; farming households
5. Pollution Outcome Monitoring	Track environmental and social outcomes beyond installed-capacity metrics	Avoided emissions reporting; electrification rates; household energy surveys; air quality monitoring	State energy and environment agencies

Conclusion

This paper will introduce a space-specific secondary-data evaluation of the position of solar power in pollution decrease and sustainable development in Uttarakhand. These results show that the implementation of solar PV can have a significant role to play by cutting the carbon emission into the atmosphere, decreasing the reliance on coal-based grid power, enabling cleaner household energy transitions, enhancing the resilience of infrastructure, and providing livelihood in a state where these outcomes are particularly important. The quantitative estimates that have been created here, about 0.66 Mt CO_2/year prevented under current capacity and about 2.87 Mt CO_2/year at the 2028 objective, are concrete foundations of how solar expansion can be considered against its professed sustainability ambitions. It is not a small number considering that this is a mountain state with a high ecological conscience and relatively low industrial emissions. However, the paper also stresses that such advantages are conditional. They rely on the deployment being organized on the basis of ecological intelligence, social inclusion, and institutional integrity.

The topography of Uttarakhand does not allow a generic solar-park model. Scarcity of land, ecological responsiveness, fragility of terrain, seasonal variability as well as the specific vulnerability of remote hill communities impose adaptation needs of project design and policy instruments. The able-to-respond to these realities in the five-pillar Regional Clean Solar Transition Model proposed here is rooftop-first deployment, remote energy justice in mini-grids, environment-screened utility projects, solar-linked livelihood programmes, and pollution-outcome monitoring. The greater theoretical input of the given paper is to prove that the evaluation of solar energy in a multi-dimensional mountain state cannot be achieved without multi-dimensional sustainability prism that takes energy engineering or emission accounting out of context. In Uttarakhand, solar power is not a simple technology of generating electricity. It is a possible tool of pollution alleviation, social justice, climate stability, and ecological security- but only in the case it is designed this way. A solar target achievement of 2028 in the state, pursued with this orientation, has the potential to transform this one of the most ecologically important and climate vulnerable landscapes in India into a sustainable development.

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