Managing ecological risks of renewable energy expansion in arid regions

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Received: November 4, 2025; Accepted: May 21, 2026; Published Online: June 1, 2026; https://doi.org/10.59717/j.xinn-geo.2026.100234

Citation: Sun F., Feng Q., Xiao J., et al. (2026). Managing ecological risks of renewable energy expansion in arid regions. *The Innovation Geoscience* **4**:100234.

The development of large-scale renewable energy bases in the desert areas of China represent a central strategy for achieving the dual-carbon goals and facilitating energy structure transformation.[1] According to the National Energy Administration, by 2023, the five northwestern provinces—Inner Mongolia, Gansu, Xinjiang, Qinghai, and Ningxia—had capitalized on abundant wind and solar resources, installing over 185 GW of photovoltaic (PV) capacity and integrating more than 127 GW of wind power into the grid, increased by 32.7% year-on-year. Major installations, such as those in the Tengger Desert in Inner Mongolia Autonomous Region, the Hexi Corridor in Gansu Province, and the northern foothills of the Tianshan Mountains in Xinjiang Uygur Autonomous Region, each feature gigawatt-scale capacities and serve as strategic pillars of the national clean energy supply.[2] Alongside the construction of these bases, systematic ecological restoration measures were implemented, including desertification control, sand stabilization, vegetation recovery, and water resource management. These initiatives advanced the demonstration of "PV + desert control" models in regions such as Kubuqi and Ulan Buh.[3] A second batch of planned large-scale renewable energy bases in the desert, gobi and desertification areas is projected to achieve a total capacity of 455 GW,[2] extending into ecologically sensitive regions such as the Qinghai–Tibet Plateau.

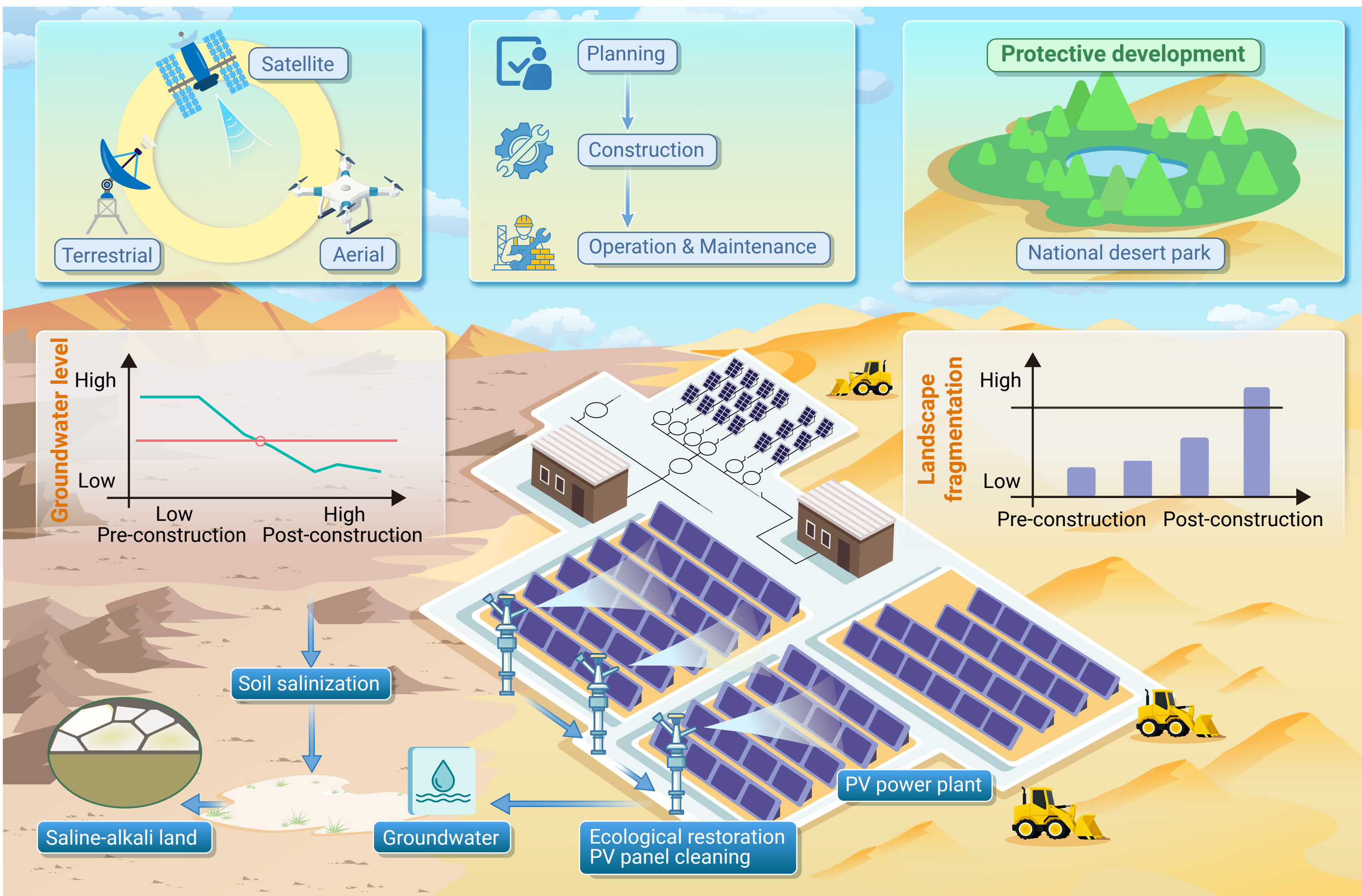

Figure 1. Ecological risks and mitigation strategies for the deployment of PV power plants in arid regions.

The development of large-scale renewable energy bases in the desert areas, while advancing clean energy transitions, confronts multiple ecological challenges (Figure 1). Large-scale development in arid regions tends to exacerbate water resource conflicts. While the development of new water-saving technologies is a key focus of PV projects, these technologies may not be deployed at scale in the short term. The "Kubuqi desert" model exemplifies this issue, where excessive water use raised sustainability concerns.[4] Long-term impacts may include groundwater depletion and soil salinization, rendering this model unsuitable for replication in other water-scarce regions. Geomorphic modifications cause irreversible damage to pristine ecosystems. Sand dune leveling eliminates dune–interdune composite habitats, resulting in the loss of endemic species,[5] and disrupts aeolian processes by altering surface roughness, which may intensify wind erosion.[6] Spatial planning deficiencies are evident in the disordered expansion into desert interiors, creating systemic risks. Particularly in ecologically vulnerable zones like the Qinghai–Tibet Plateau, extensive development ignoring surface heterogeneity, climatic variations, and precipitation gradients may initiate ecological chain reactions. The prevailing campaign-style construction approach highlights major planning shortcomings, with some projects proceeding without complete scientific validation. Intensive construction-related land disturbance, combined with delayed ecological restoration, risks perpetuating the "develop first, remediate later" paradigm.

Future national initiatives for developing large-scale renewable energy bases in the desert areas must employ systematic approaches and precautionary principles to reform development paradigms, with ecological security at the core of energy policy decisions. First, top-level design requires enhancement and integration with territorial spatial planning through the establishment of a nationally unified negative list and ecological redline system for renewable energy development in these areas. This system should define restrictive development provisions for extremely vulnerable zones such as the Qinghai–Tibet Plateau, establishing differentiated development thresholds based on precipitation gradients, underlying surface characteristics, and water resource carrying capacity.
Second, a multi-tiered collaborative governance mechanism must be instituted through legislative measures to improve coordination among energy, environmental, and water resource authorities. This entails implementing a cross-departmental joint approval system encompassing the entire project lifecycle from planning through construction and operation, requiring the integration of ecological restoration budgets and implementation into project planning from the outset. Technically, a compulsory national standard system should be developed specifying ecological disturbance control metrics for photovoltaic array configurations, vegetation recovery benchmarks, and upper limits for water resource consumption. Principles including water-determined greening", "low-impact construction", and Nature-based Solutions (NbS) must be translated into quantifiable engineering parameters. For sensitive ecological units (e.g., mobile sand dunes and desert-oasis transition zones), protective development models should be implemented through measures such as designating national desert parks and preserving natural geomorphic corridors to maintain desert ecosystem integrity.

Furthermore, the dynamic monitoring and compensation mechanism should be improved, and a national ecological risk early warning platform should be established based on the space-air-ground integrated monitoring network. In addition to monitoring and issuing early warnings for dust events that substantially affect clean energy production, monitoring and early warning of ecological risks should also be implemented. On the one hand, long-term monitoring should be performed on regional flora and fauna following the development of large-scale new energy bases. On the other hand, long-term monitoring and evaluation should be conducted to assess the effectiveness of sand control and ecological restoration practices. Major energy bases should conduct annual ecological audits, with assessment results linked to local government performance evaluations and project electricity tariff subsidies. Nationally, coordinated energy-ecological planning should prioritize "green power-ecology" integrated bases near urban desert peripheries while strictly regulating uncontrolled expansion into desert interiors. Through dedicated national research initiatives for renewable energy in arid regions, critical technological bottlenecks, including water-conserving sand stabilization techniques and microclimate regulation for wind-solar farms, must be overcome to transform ecological restoration from a cost burden into a value-generating enterprise. Ultimately, these measures will establish a sustainable development pathway characterized by "strict ecological constraints, precision development planning, standardized governance technologies, and long-term regulatory oversight", enabling a strategic shift from reactive desert control to proactive desert conservation in energy development. This multidimensional strategic framework, through the systematic integration of spatial adaptation and process control, establishes a scientific paradigm for reconciling energy with ecological security, presenting the model for renewable energy development of China in global arid regions.

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FUNDING AND ACKNOWLEDGMENTS

This work was financially supported by Gansu Provincial Science and Technology Planning Project (23ZDFA018 and 25YFFA007); Western Light Project of Chinese Academy of Sciences (xbzglzb2022018); and the UK Royal Geographical Society with Institute of British Geographers Thesiger-Oman Fellowships grant (THES 03.26). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

AUTHOR CONTRIBUTIONS

All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.