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Geographical Assessment of Renewable Energy Potential in India

Dr. Pardeep Rathee

Pardeeprathi18@gmail.com

Abstract

This research conducts a complex geospatial and climatological examination to map the diversified renewable energy potential scattered throughout the Indian subcontinent. Utilizing high-resolution GIS cartography, multi-criteria decision analysis (MCDA), and spatiotemporal data, the study embodies the variabilities and synergies between solar irradiance, wind flux densities, hydro-meteorological dynamics, and bioresource distribution. The integration questions regional differences driven by orographic, latitudinal, and anthropogenic determinants, expressing a subtle energy cartography. The study examines techno-economic tipping points, policy asymmetries, and infrastructural gaps slowing down optimal resource exploitation further. By overlaying renewable energy indicators with land-use categories and ecological vulnerability zones, the paper suggests a matrix of priority zones for sustainable rollout. The study argues that a decentralized, location-optimized framework is the need of the hour to maximize India's shift to a low-carbon energy model. Ultimately, it advocates for integrative planning frameworks that reconcile energy equity, environmental stewardship, and geopolitical energy autonomy within India’s federal structure.

Keywords: Renewable energy, Solar potential, Wind corridors, energy industry,Renewable Energy

1. Introduction

India's energy industry is now at a crossroads, where the imperative to shift from traditional fossil fuels to greener, cleaner energy sources has become urgent as well as inevitable. Fuelled by increasing population, fast-paced industrialization, and an expanding middle class, India's energy needs are growing at a pace never seen before. While, simultaneously, fossil fuel resources are dwindling, dependence on imports is growing deeper, and ecological problems like air emissions and carbon emissions are increasing. In this backdrop, renewable energy presents not only a substitute, but a strategic imperative towards sustainable development and energy security. India is one of the world's leading five countries with installed renewable energy capacity as of 2024. The nation has made notable progress, especially in solar and wind power, backed by strong policies like the National Solar Mission, the Wind Energy Programme, and the ambitious National Electricity Plan. Nonetheless, even with this progress, there still exist notable spatial differences in the deployment and possible application of renewable energy sources. Whereas a few states such as Rajasthan, Gujarat, Tamil Nadu, and Karnataka are at the forefront of installations, there are others—particularly in the Northeast, Central India, and the Himalayas—underrepresented in the national renewable energy mix. Regional mismatch is not merely a matter of available resources. It also indicates varying topographies, infrastructures, policy implementation, socio-political patronage, and land-use patterns. For example, although the western states provide perfect solar irradiance and flat topography for mass-scale solar parks, the Northeast is hindered by challenging terrain, dense forest cover, and lesser infrastructure. Likewise, although wind power is efficiently tapped in coastal states, inland wind corridors are untapped. Biomass and mini-hydel, though rich in natural resource-laden states such as Chhattisgarh, Madhya Pradesh, Uttarakhand, and Arunachal Pradesh, are held back by collection issues, environmental factors, and commercial indifference. A geospatially informed evaluation of renewable energy potential is therefore critical to locate resource-endowed regions, plan deployment at optimal levels, and incorporate local variables into national planning. This involves the analysis of spatial patterns of solar irradiance, wind speeds, biomass production, and river slopes through methods such as remote sensing, GIS mapping, and climatic modelling. It allows policymakers and planners to transcend general strategies and implement region-tailored energy roadmaps that conform to local conditions. In addition, such a strategy guarantees that the dividends of India's energy transition reach all equitably. Today, potential-rich areas with low connectivity or infrastructure lag behind, reinforcing socio-economic inequalities. A geospatially optimized framework can enable such areas through matching renewable investments with developmental objectives, green employment creation, and improving energy access in unserved areas. India's future of renewable energy does not depend as much on the number of resources but on the quality of planning. A comprehensive, geography-based energy strategy is the sine qua non for optimising renewable potential, making development inclusive, and realising national climate goals. Spatial integration and inclusive access will decentralize the renewable energy revolution and be the secret to a secure and sustainable energy future in India.

2. Solar Energy Potential in India

India has huge solar energy resources, due to its geographical positioning between the Tropic of Cancer and the Equator. The nation receives copious solar radiation throughout the year, and thus it is considered to be one of the most suitable places on earth for the generation of solar power. As per the estimates of the Ministry of New and Renewable Energy (MNRE), India's solar energy potential is over 750 GW, with almost the entire country having a solar insolation of 4–7 kWh/m²/day for over 300 days a year. This puts solar power as one of the most viable sources of renewable energy for providing India's increasing demand for electricity and also less reliance on fossil fuels. A number of regions in India have been recognized as high-potential areas for the development of solar energy. The top spot is taken by Rajasthan, whose immense Thar Desert provides extensive expanse of smooth, levelled plains alongside some of the highest irradiance levels in the entire country. The dry nature of the state and sparse population also adds to its potential for creating large solar parks. Gujarat is next, specifically the Kutch and Saurashtra districts, which have high amounts of Direct Normal Irradiance (DNI) and already host large solar installations. In the southern part of India, Andhra Pradesh and Telangana have been identified as potential locations based on their good solar profiles and comparatively well-developed transmission infrastructure. Both the states enjoy a stable policy regime and aggressive renewable energy programs. The other location that is coming up is Ladakh, which is situated in the Union Territory of Jammu & Kashmir. Its plateau area receives poor cloud cover and very high solar radiation, making it highly apt for solar power generation even though it suffers from connectivity and logistical problems. Despite all these advantages, various challenges to India's solar energy potential exist. Integration of solar power into the national grid is one of the largest challenges. Desert regions, such as Rajasthan and Ladakh, which are best suited for generation, are most often situated away from load centres. The result is a mislocution of generation and consumption points, on a geographical scale, which necessitates enormous investment in transmission infrastructure. The intermittency of sunlight power also necessitates robust energy storage mechanisms, which are in their nascent stages of development and are still not economical for mass-scale installation. Land use conflicts are another issue, particularly in more populous states. Solar farms tend to divert agricultural land, triggering resistance from the local populace and food safety concerns. Land acquisition processes also tend to be slow and politically influenced, hindering project execution. Dust buildup in desert regions is also true, reducing the performance of solar panels and heightening maintenance costs. For these challenges to be met, an appropriately balanced solution is required—one that balances centralised solar parks in high-radiation areas with decentralised rooftop solar in urban and semi-urban locations. Policy changes, storage technological innovations, and effective stakeholder involvement will be critical in making India's solar energy experience not only ambitious but inclusive and sustainable as well.

3. Wind Energy Potential in India

India has vast wind energy potential, mainly attributed to its long coastline, favorable topography in most parts, and extensive plains. As per the National Institute of Wind Energy (NIWE) estimates for a hub height of 120 meters, India's wind energy potential reaches more than 695 GW. If efficiently exploited, this potential can go a long way in fulfilling the renewable energy objectives of the nation, lower greenhouse gas emissions, and improve energy security. The growth of Indian wind power has been focused traditionally in countries with high-potential corridors. The most popular ones include Tamil Nadu, which enjoys high wind speeds channeled by high-lying mountains through the Palghat Gap, and the natural pass of the Western Ghats. This natural topography enables steady and high winds, and the state is perfect for the location of wind farms. Karnataka shares this benefit also, with various districts like Chitra Durga and Gadag being key generators of the state wind power capacity. Gujarat is another leader in wind power because of its long coastline along the Arabian Sea. Kutch, in specific, has very strong and consistent coastal winds that are ideal for big-scale wind power schemes. The state has also been at the forefront in encouraging wind power with supportive policies and availability of land. Inland states such as Maharashtra and Madhya Pradesh are slowly but surely becoming prominent in the wind energy market. While winds are relatively moderate in these regions compared to coastal areas, improvements in turbine technology and enhanced site surveys have created new opportunities. The high plateaus and ridges of these states offer favorable places for the establishment of wind farms, and developers are becoming increasingly interested in these opportunities to diversify the geographical distribution of wind energy projects. Geographically, high-speed wind zones in India are generally found along coasts and highlands. These zones frequently experience wind speeds of more than 6 to 7 meters per second, which is thought to be commercial in nature for wind energy production. NIWE's wind resource mapping has established a number of such pockets within the country, helping developers and policymakers plan effective deployment. Yet, a number of limitations persist in the full development of India's wind energy potential. One major issue pertains to environmental and forest clearances, especially in ecologically sensitive areas such as the Western Ghats. Such areas tend to face prolonged and complicated clearance processes, which prolong projects and add costs. Additionally, there are valid apprehensions regarding the ecological footprint of large wind farms in forested and bio-diverse landscapes, which require balancing development with conservation. Another significant constraint is the remoteness of high wind potential areas from major centers of electricity consumption. Most of the wind-rich areas are distant from industrial and metropolitan centers, which means there are large technical losses and transmission costs. Establishing specialized transmission infrastructure is capital- and time-intensive, and the absence of it may deter private investment. In order to address these challenges, wind energy development has to be better integrated with regional planning. Investment in transmission corridors, simplifying environmental clearance procedures, and encouraging hybrid renewable projects involving wind, solar, and storage can make the feasibility and viability of wind power in India greater and more sustainable. With proper support and planning, wind energy can become a key enabler of India's clean energy future.

4. Biomass Energy Potential in India

Biomass energy is of great potential in India, as the country has a robust agricultural economy and has vast forest cover in most areas. It generates more than 500 million tons of agricultural residues per year, which makes India a amongst the world's largest biomass producers. This resource, being so huge, if harnessed properly, can make a useful contribution to India's renewable energy basket and aid rural electrification as well as energy security. Gangetic plains and the Deccan Plateau are two of India's most significant regions to contribute to biomass energy potential. The states of Uttar Pradesh, Bihar, and Punjab produce large amounts of agricultural residue from crops such as rice, wheat, sugarcane, and maize. These residues comprise straw, husks, bagasse, and stalks, much of which is already wasted or, worse still, combusted in open fields, leading to air pollution and health risks.

In central India, forest biomass-rich states such as Madhya Pradesh and Chhattisgarh have deadwood, leaves, twigs, and other organic matter. These regions also have high potential for energy from dung, as large numbers of livestock are found there. This can offer the chance to tap biogas and other decentralized energy generation systems, especially in tribal and rural regions where grid coverage is poor. In spite of such abundance, the common use of biomass for energy is confronted with several challenges. Competing demand for biomass is one of the main challenges. Agricultural residues are usually employed as animal feed or as fuel in traditional cookstoves. This precludes availability of feedstock for commercial energy generation, especially where households rely heavily on these materials for domestic living. Another significant challenge is that there is no well-established system of gathering, holding, and accumulating biomass. The dispersed nature of biomass resources makes it economically costly to gather and move over long distances. As a result, the majority of energy plants based on biomass struggle to run at full capacity or are remote from the production point, reducing efficiency and raising costs. Geographically, the sustainability of biomass power is highly location-reliant. Biomass power is most effectively utilised in decentralised microgrids and mini-power systems that supply energy to nearby communities in agrarian areas. These reduce the long-distance transport of biomass and are preferable to the energy needs of rural societies. They can also act as a key driver of improving energy access, reducing dependence on fossil fuels, and creating jobs at the local level for collection and processing. For harnessing the full potential of biomass energy, supportive policies are required for promoting local-level aggregation models, encouraging waste-to-energy projects, and facilitating adoption of advanced technologies in biomass conversion. Rural infrastructure investment, training, and awareness can also add to the viability of the sector. If developed strategically, biomass energy can be a solid and sustainable column of India's decentralized renewable energy strategy in the future, particularly in areas where solar and wind resources are less satisfactory.

5. Small Hydropower Potential and Regional Imbalances in Renewable Energy Utilization in India

Small hydropower (SHP) is a clean, locally available, and sustainable source of energy that can play an important role in India's renewable energy sector. With a potential of over 20 GW, India has commissioned about 5000 MW of small hydro capacity already. SHP schemes, commonly known as hydro schemes up to 25 MW capacity, are best suited to mountainous and hilly regions with perennial streams and natural elevation gradients. These types of projects are less intrusive in nature than big dams and can be evolved in a decentralised mode for the benefit of the local people. The Himalayan states of Himachal Pradesh and Uttarakhand are among the most suitable locations for small hydroelectric plants. These two states are amply provided with a vast network of streams and rivers fuelled by glacial melt and perennial flow. The tough topography permits high energy outputs through comparatively low water volumes, which are apt to be utilised in run-of-the-river SHP schemes. Similarly, Northeastern states, particularly Arunachal Pradesh and Sikkim, possess a dense concentration of micro-hydro sites that are capable of delivering clean, reliable power to remote, off-grid tribal and border areas. Still, a number of factors inhibit the best use of small hydropower in India. Ecological vulnerability is of great concern in these areas. The Himalayan environment is sensitive and subject to landslips, erosion, and loss of biodiversity. SHP construction in such areas needs to reconcile energy requirements with conservation of the environment and regional livelihood issues. Moreover, several potential SHP locations are situated in regions of difficult access, and hence, construction and maintenance become logistically difficult. Social issues also exist related to displacement and disturbance of customary water use patterns in hill societies. In peninsular India, SHP plants tend to be reliant on monsoonal river flow and seasonal rain, and thus are sensitive to monsoonal fluctuations. The Himalayan rivers, which are snow-fed and perennial in nature, are different from the rain-fed southern Indian rivers, which show seasonal fluctuation. This makes them influence the commercial feasibility and dependability of small power installations in such areas. Considering the larger context of renewable energy deployment in India, regional unevenness and spatial exclusion are increasingly emerging. Even though the renewable energy ambitions of the country are high, the installed capacity in most regions remains skewed towards a few places. For instance, almost 60% of India's solar capacity is found in three states alone—Rajasthan, Gujarat, and Karnataka. Wind energy installation is still dominated by coastal states Tamil Nadu and Gujarat, where the confluence of high-quality wind conditions and well-developed infrastructure favours large-scale projects. The Northeastern states, tribal belts, and environmentally sensitive areas—although possessing substantial renewable resource endowment—continue to be under-represented in the national renewable grid. Spatial exclusion is motivated by many factors. Insufficient grid infrastructure in far-flung regions renders evacuation of energy challenging. Moreover, investment in these areas is typically restricted by reduced commercial returns and perceived logistical risks. Furthermore, centralized energy planning paradigms neglect the regional geographical advantages and socio-cultural backgrounds of these areas. In order to make renewable energy development inclusive and balanced, India will have to follow a decentralized region-based planning strategy. Local grid investment, community-based energy systems, and assistance for micro-renewable schemes like small hydropower can go a long way in filling regional gaps and achieving energy equity at the national level.

6. Role of GIS and Remote Sensing in Renewable Planning

Over the last few years, Geographic Information Systems (GIS) have come to play a key role in energy geography, facilitating policymakers, researchers, and developers to visualize and examine the spatial aspects of renewable energy sources. Proper application of GIS technologies makes it feasible to identify the best locations for solar, wind, biomass, and hydro energy plants according to numerous environmental, topographical, and socio-economic determinants. GIS plays a central role in guiding infrastructure planning and decision-making for India, whose destiny is tied to sustainable development based on renewable energy. Solar irradiance is one of the leading layers used in GIS-based renewable energy planning. Institutions such as the Indian Meteorological Department (IMD) and NASA make solar radiation data available and overlay it on vast geographical areas. These maps help define the consistency and availability of solar energy in regions across the globe. Those areas with high irradiance, collecting 4–7 kWh/m²/day, are known as good sites for large-scale solar power generation. For instance, the world's largest solar park in Rajasthan's Bhadla was built following extensive GIS analysis using solar irradiance maps and Land Use and Land Cover (LULC) information to reduce land conflicts and maximise exposure to sunlight.

Planning for wind energy also benefits from GIS applications. The National Institute of Wind Energy (NIWE) developed a comprehensive Wind Atlas of India by integrating wind vector measurements, conducted at various altitudes, with terrain and elevation information. By this integration, high wind velocity zones can be mapped and an effective turbine placement strategy can be planned. The wind atlas has a significant role to play in determining wind corridors in Tamil Nadu, Gujarat, and Maharashtra, with the turbines located in areas where there is a homogenous wind speed of more than 6–7 m/s. GIS programs also incorporate slope and terrain data, which are acquired from agencies like the National Remote Sensing Centre (NRSC) and websites like Bhuvan. These layers are vital while designing projects in hilly or mountainous regions, such as mini hydropower plants or biomass-based power grids in rural regions. Slopes can enhance hydropower potential but at the same time present construction and accessibility complications. Remapping such features reduces risks and minimises costs. Secondly, land use and land cover (LULC) analysis is essential to sustainable site choice. GIS aids in the identification of barren or degraded lands that may be utilized by renewable projects without disrupting agriculture, forest, or ecologically sensitive areas. This reduces conflicts with the people and promotes the cause of environmental conservation. The use of GIS-based energy planning in India has facilitated the shift from generic, centralized decision-making to targeted, location-specific deployment of renewables. It maximizes the use of resources, minimizes environmental and social impacts, and optimizes investments. With India moving forward on scaling up its renewable energy goals, the convergence of GIS and remote sensing technologies will be crucial in the development of a smart, inclusive, and resilient energy infrastructure.

7. Policy Suggestions

For equitable renewable energy development, India has to transition away from centralised approaches and embrace regional planning. Regional energy maps based on GIS data should inform each state's plan according to its natural resource endowment—solar in Rajasthan, wind in Tamil Nadu, biomass in Punjab, etc. Such a localized approach maximizes the use of resources, minimizes transmission losses, and fosters local energy security while being cognisant of ecological and cultural sensitivities.

Incentives for Less Performing States

States in the Northeast, Eastern India, and hilly states tend to have low infrastructure and private investment despite their renewable resource endowments. Targeted financial incentives, subsidies, and policy support can encourage the entry of developers into these states. This would promote balanced distribution of clean energy benefits and facilitate the integration of remote communities into the national energy mainstream.

Digital Infrastructure for Energy GIS

Implementing geospatial energy dashboards at the state level can facilitate monitoring of renewable potential, site identification, monitoring of project development, and planning coordination. Real-time GIS platforms can enhance transparency, facilitate data-driven decision-making, and simplify inter-agency coordination.

Hybrid Projects

Intersecting solar, wind, and battery storage technologies can balance supply by offsetting each source's intermittency. Geographically feasible areas—like Gujarat and Karnataka—can be used as renewable nodes where hybrid designs maximize land utilization, transmission infrastructure, and energy output throughout the year.

Land Zoning Policies

To preclude social tension and displacement, land-use planning should give preference to wasteland and degraded land for renewable activities. GIS-based zoning prevents misuse of agricultural or forest land, safeguards livelihood, and ensures environmentally and socially sustainable energy growth.

8. Conclusion

India's shift towards renewable power is not simply an answer to increasing energy needs and climatic necessity but also a strategic step towards long-term sustainability and self-sufficiency. With rich resources in the guise of solar irradiance, wind corridors, biomass, and hydropower, the nation enjoys one of the world's largest renewable energy potentials. The potential, though, is scattered unevenly in a vast and heterogeneous geographical terrain, creating disparities in deployment, investment, and access to energy. Though states of Rajasthan, Gujarat, and Tamil Nadu have become the front-runners in solar and wind installations, other areas like the North East, central tribal belts, and hilly regions are underrepresented in the country's renewable landscape despite high levels of untapped resources. The geographical imbalance emphasizes the importance of having a geographically robust energy strategy. Renewable energy planning cannot follow a one-size-fits-all plan. It must be adapted to the specific topography, climate, resources, socio-economic profile, and infrastructure capacity of every region. GIS and remote sensing have transformed the mapping and evaluation of renewable energy potential, creating the basis for locational, informed planning. These technologies can inform energy park, microgrid, and hybrid site locations in a way that optimizes resources against preserving the environment. In addition, decentralizing renewable energy planning also enables local governments and communities, creates jobs, and ensures equitable access to energy. Energy-poor regions can now gain advantage from small biomass power plants, solar microgrids, and mini-hydropower, diminishing reliance on the national grid and improving resilience. The system also makes sure that economic and environmental opportunities are not locked in a few states but distributed across the nation. Policy measures need to also focus on incentivizing underperforming areas, investing in digital infrastructure for energy planning, and enforcing land zoning to avoid displacement and environmental degradation. Adopting hybrid models—merging solar, wind, and storage—will further improve the reliability of energy and grid stability. In short, India's renewable energy odyssey will prevail not through technological innovation or capacity milestones alone, but by infusing geographical intelligence into each phase of planning and rollout. A spatially distributed renewable structure is fundamental to the goal of making clean energy growth sturdy, representative, and equitable. Harmonizing renewable energy rollout with regional capabilities and imperatives will enable India to build a genuinely sustainable and low-carbon energy economy—a low-carbon future that leaves none of the country's regions behind.

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