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THE ROLE OF ZONAL RESEARCH IN ADVANCING RENEWABLE ENERGY SOLUTIONS

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Abstract:

The transition to renewable energy is crucial in addressing Pakistan's growing energy needs while mitigating environmental degradation. However, a uniform approach to renewable deployment often overlooks the diverse climatic, geographic, and socio-economic conditions across the country. Zonal research—geographically targeted studies tailored to specific regions—has emerged as a vital framework in developing context-specific renewable energy solutions. This article explores how zonal research enhances decision-making in the selection, implementation, and optimization of renewable energy technologies such as solar, wind, biomass, and micro-hydel systems. Through a multidisciplinary lens, the study synthesizes data across Pakistan's four major zones (North, South, East, and West) and illustrates how localized insights can facilitate more sustainable and resilient energy infrastructures. The paper also provides empirical data, visualized through comparative graphs, to highlight the potential for zonal integration in national energy policy.

Keywords: *Zonal Energy Research, Renewable Energy Policy, Regional Energy Optimization, Energy Sustainability in Pakistan*

INTRODUCTION

Pakistan's energy sector continues to struggle with inefficiencies, heavy reliance on imported fuels, and underutilized renewable resources [1]. Despite abundant solar irradiation in Sindh and Balochistan [2], and strong wind corridors in southern Pakistan [3], a lack of zonal customization in policy and planning hampers progress. Zonal research allows for tailored energy strategies that maximize local resource potential, align with regional energy needs, and ensure socio-technical acceptability [4][5]. This article investigates the role zonal studies play in shaping adaptive and data-driven renewable energy deployment.

1. Zonal Resource Mapping and Classification

A critical foundation for advancing renewable energy deployment in Pakistan lies in understanding the country's diverse climatic zones and their corresponding energy potentials. Zonal research enables a targeted approach that aligns energy solutions with the specific environmental, geographic, and socio-economic conditions of each region.

Climatic Zones and Energy Potential

Pakistan can be broadly categorized into four major energy zones:

- **Northern Zone (Khyber Pakhtunkhwa and Gilgit-Baltistan):**
Known for its mountainous terrain and perennial rivers, this region is ideal for micro and small-scale hydropower due to consistent water flow and elevation gradients. Solar energy potential is moderate, constrained by seasonal cloud cover and shorter daylight hours.
- **Southern Zone (Sindh and Southern Balochistan):**
This zone receives abundant solar radiation and hosts some of the country's most prominent wind corridors. With clear skies year-round and strong coastal winds, it is optimal for large-scale solar PV farms and wind energy parks.
- **Eastern Zone (Punjab):**
Punjab's rich agricultural output makes it highly suitable for biomass-based energy production. Additionally, its southern parts enjoy significant solar exposure, supporting utility-scale solar installations.
- **Western Zone (Interior Balochistan):**
Characterized by arid landscapes and low population density, this zone offers high solar irradiance, making it ideal for decentralized off-grid solar solutions, especially for remote and underserved communities.

GIS-Based Mapping and Data Analytics

The integration of Geographic Information Systems (GIS) and data analytics has revolutionized renewable energy planning. By overlaying climatic, topographic, and infrastructural data, GIS tools provide comprehensive insights into regional energy potentials. Through this approach, decision-makers can:

- Generate high-resolution solar maps to pinpoint optimal photovoltaic deployment zones.
- Create wind speed profiles across different altitudes to identify high-performance wind turbine sites.
- Analyze hydrological flow patterns to locate viable micro-hydro power generation points.
- Estimate biomass production through crop residue mapping and agricultural intensity.

This spatially-informed strategy not only enhances technical efficiency but also improves investment decision-making and regional planning alignment.

Figure: Renewable Resource Potential by Zone (Illustrative Annual Capacity in MW)

Zone	Solar (MW)	Wind (MW)	Hydropower (MW)	Biomass (MW)
Northern (KP/GB)	1,500	200	5,000	400
Southern (Sindh/Balochistan)	15,000	20,000	800	700
Eastern (Punjab)	8,000	2,500	1,200	4,500
Western (Interior Balochistan)	10,000	1,200	500	300

This mapping and classification framework lays the groundwork for aligning renewable energy technologies with regional strengths, ensuring a more efficient, equitable, and sustainable energy future for Pakistan.

2. Technology Suitability and Regional Matching

To maximize efficiency, cost-effectiveness, and environmental benefits, renewable energy technologies must be matched with the regional characteristics of Pakistan’s diverse zones. This zonal approach enhances implementation success by leveraging natural advantages and aligning with local socio-economic realities.

Solar PV in Arid Zones

Arid regions in southern Pakistan, particularly in Sindh and Balochistan, receive high solar irradiance levels, exceeding 5.5 kWh/m²/day for over 300 days a year. These conditions make them highly suitable for photovoltaic (PV) solar farms and off-grid solar mini-grids. Flat terrains facilitate easy installation, while low precipitation reduces system degradation.

Key benefits include:

- Minimal shading and dust-related challenges with proper panel elevation and cleaning systems
- Potential for hybrid setups combining solar with battery storage in remote areas
- Use in water pumping for agriculture via solar-powered tube wells

This zonal match significantly reduces energy poverty in areas where grid connectivity is limited or unreliable.

Wind Energy Feasibility in Coastal Zones

The coastal belt of Sindh, especially between Gharo and Jhimpir, offers one of Pakistan’s most promising wind resources. Average wind speeds exceed 7 meters per second, providing high-capacity factors for modern wind turbines.

Key advantages include:

- Stable wind patterns due to the coastal microclimate
- Large land parcels available for wind farm clusters

- Proximity to existing transmission infrastructure, enabling grid integration

The southern corridor is already home to multiple commercial-scale wind farms and continues to attract investment for expansion under zonal renewable energy policies.

Biomass in Agricultural Belts

Punjab's dense agricultural landscape generates large quantities of crop residues (e.g., wheat straw, rice husk, sugarcane bagasse), which can be converted into energy through biogas plants, biomass combustion, or biofuel production.

Regional matching advantages:

- Year-round availability of feedstock due to multiple cropping cycles
- Proximity to rural populations in need of energy for cooking, heating, and farming
- Opportunity to convert agricultural waste into clean energy, reducing open-field burning

Biomass technology deployment in these belts can also stimulate local green jobs and sustainable agrarian entrepreneurship.

Micro-Hydro in Mountainous North

The hilly terrain of Khyber Pakhtunkhwa (KP) and Gilgit-Baltistan (GB) is rich in fast-flowing streams and rivers. This makes it ideal for micro- and mini-hydro power plants, which use low-head water flow to generate clean electricity for remote and dispersed settlements.

Distinct regional benefits:

- Minimal ecological disruption compared to large dams
- Community-managed systems suitable for off-grid electrification
- Cost-effective energy solutions with high social acceptance

This technology has already improved rural livelihoods and education access by powering homes, schools, and health centers in hard-to-reach areas.

3. Zonal Policy Design and Investment Frameworks

Effective deployment of renewable energy technologies across Pakistan's distinct regions requires zonal policy alignment and a targeted investment ecosystem. This involves designing regulatory frameworks, fiscal incentives, and partnerships that reflect regional resource availability, infrastructure readiness, and socio-economic contexts. A zonal lens ensures that energy policies are equitable, context-sensitive, and results-driven.

Regional Subsidies, Incentives, and Regulatory Models

One-size-fits-all policies often fail to address regional disparities. Therefore, zonal differentiation in subsidies and incentives can catalyze localized energy growth by accounting for the unique challenges and opportunities of each region:

- **Southern Zones (e.g., Sindh and Balochistan):**

High solar and wind potential justify capital cost subsidies for large-scale solar PV and wind parks, as well as feed-in tariffs for off-grid applications.

- **Eastern Zones (e.g., Punjab):**
Incentives for biomass-to-energy projects can reduce stubble burning and encourage sustainable agricultural practices. This includes zero-interest financing, tax exemptions, and technology import subsidies.
- **Northern Zones (e.g., KP and GB):**
Given terrain challenges, micro-hydro and hybrid microgrid incentives are essential. Custom zonal net metering policies, grants for community-based hydropower, and training programs for local technicians are recommended.
- **Western Zones (e.g., Interior Balochistan):**
Prioritize decentralized off-grid electrification policies, especially through solar mini-grids. Logistical subsidies and security incentives for private investors can mitigate operational risks in remote regions.

Such zonal targeting allows provincial and federal authorities to align incentives with regional capacity, thereby increasing investor confidence and ensuring inclusive energy access.

Public-Private Partnerships (PPPs) for Localized Energy

Public-private partnerships (PPPs) have emerged as powerful mechanisms to scale renewable energy while balancing risk and resources. A zonal approach to PPPs promotes context-relevant infrastructure models that can adapt to regional constraints:

- **Utility-scale wind and solar in Sindh:**
PPP frameworks have enabled multinational wind projects in the Gharo–Jhimpir corridor, where land, grid connectivity, and consistent wind patterns attract long-term investors.
- **Biomass co-generation in Punjab:**
Partnerships between sugar mills, local governments, and renewable tech providers have led to co-generation plants, utilizing bagasse and crop residues for power and heat.
- **Microgrids in KP and GB:**
Community-centered PPPs, involving local cooperatives, NGOs, and microfinance institutions, have proven successful for micro-hydro and solar hybrid systems, ensuring both ownership and sustainability.
- **Rural energy cooperatives in Balochistan:**
Zonal energy pilot programs with shared ownership and maintenance responsibility have increased trust and longevity in renewable energy infrastructure.

A structured policy framework that enables risk-sharing, profit incentives, and community participation significantly enhances the success and scalability of zonal renewable projects.

Figure: Zonal Policy Tools and Strategic Investment Priorities

Zone	Preferred Technology	Policy Tool	Investment Strategy
Southern (Sindh/Balochistan)	Solar, Wind	Feed-in Tariffs, Capital Subsidies	Large-scale PPPs with foreign investors
Eastern (Punjab)	Biomass	Tax Holidays, Agro-Energy Incentives	Agro-industrial energy clusters
Northern (KP/GB)	Micro-hydro, Solar Hybrid	Community Grants, Localized Net Metering	Public-NGO partnerships
Western (Interior Balochistan)	Off-grid Solar Systems	Transport Subsidies, Risk Mitigation	NGO-driven decentralized models

By designing regionally adaptive regulatory frameworks and fostering zone-specific PPP models, Pakistan can achieve a more resilient and diversified renewable energy portfolio. This will not only reduce reliance on fossil fuels but also uplift remote and underserved communities through sustainable energy access.

4. Case Studies and Empirical Trends

To understand the practical implications of zonal research in renewable energy deployment, this section presents real-world case studies from different regions of Pakistan. These initiatives demonstrate how region-specific approaches have contributed to effective and sustainable energy solutions. The selected projects—ranging from solar and wind to biomass and micro-hydro—reflect the impact of zonal strategies on energy access, economic empowerment, and environmental outcomes.

Sindh Solar Initiative

The Sindh Solar Energy Project (SSEP), initiated in collaboration with provincial authorities and international donors, aims to install 400 MW of solar power across southern districts. Focused on high-irradiation areas like Tharparkar and Thatta, the project includes distributed solar systems for public buildings, mini-grids for rural communities, and utility-scale solar parks.

Key outcomes:

- Electrification of over 35,000 off-grid households
- Annual reduction of over 80,000 tons of CO₂ emissions
- Job creation through local solar technician training programs

This initiative is a leading example of leveraging zonal solar potential for inclusive and climate-resilient electrification.

Wind Corridor of Gharo–Jhimpir

The Gharo–Jhimpir Wind Corridor in southern Sindh is home to over 25 operational wind power plants, with a cumulative capacity exceeding 1,200 MW. The region’s high and stable wind speeds (6–7.5 m/s) make it one of South Asia’s most valuable renewable energy zones.

Empirical highlights:

- Capacity factor of up to 35%, well above global wind average
- Integration with the national grid via dedicated 132 kV transmission lines
- Attraction of foreign direct investment, particularly from China, Turkey, and UAE

This corridor exemplifies how zonal identification and infrastructure alignment can transform resource-rich regions into energy export hubs.

Chitral Micro-hydro Projects

Chitral, in northern Khyber Pakhtunkhwa, has implemented over 200 community-based micro-hydro plants, primarily under NGO-led models. These small-scale systems (<500 kW) are designed to serve mountainous and off-grid villages using local water resources.

Results:

- Electrification for over 120,000 residents in remote valleys
- Reduced dependence on diesel generators and firewood, enhancing air quality and forest conservation
- Promotion of local ownership, where village energy committees manage and maintain the systems

This grassroots model proves the efficacy of zonal solutions that integrate geography, community participation, and sustainability.

Punjab’s Biomass-to-Energy Models

Punjab’s agricultural output generates millions of tons of crop residue annually, particularly wheat straw, rice husk, and sugarcane bagasse. Several biomass-to-energy projects have been implemented in collaboration with sugar mills and independent power producers (IPPs).

Operational insights:

- Co-generation units produce both electricity and heat, improving energy efficiency
- Bagasse-based power plants at sugar mills supply electricity to the grid during crushing seasons
- Reduction in stubble burning through structured residue collection programs

These projects showcase the successful transformation of agricultural waste into clean energy, aligning with circular economy principles and sustainable farming.

5. Strategic Recommendations and Future Pathways

To institutionalize the progress made through zonal renewable energy efforts, Pakistan must embed regional differentiation into its national energy governance, research architecture, and community-level programs. The following strategic recommendations present scalable, inclusive, and future-focused pathways for advancing renewable energy development through zonal research integration.

Zonal Integration in NEPRA and AEDB Frameworks

Pakistan’s energy regulators—the National Electric Power Regulatory Authority (NEPRA) and the Alternative Energy Development Board (AEDB)—should evolve from generalized frameworks to region-sensitive governance models.

Key strategies include:

- Mandatory zonal impact assessments for all proposed renewable projects
- Development of zonal Renewable Portfolio Standards (RPS) that assign renewable targets based on local resource potential
- Creation of zonal feed-in tariffs and net metering rules customized to regional generation profiles and demand
- Institutionalization of zonal energy data hubs to track real-time performance, grid connectivity, and environmental outcomes

These shifts would ensure data-driven, regionally optimized policymaking, addressing disparities in energy access, capacity utilization, and investment attraction.

Establishing Regional Energy Research Clusters

Academic institutions and think tanks across Pakistan should collaborate to form regional energy research clusters, supported by both federal funding and international grants.

Objectives of these clusters:

- Conduct locally relevant technology trials and performance evaluations (e.g., wind speed modeling, solar panel durability under dust exposure)
- Develop open-access zonal energy databases for public and private sector use
- Provide policy guidance and innovation incubation tailored to local challenges (e.g., cold climate PV systems for Gilgit, mobile biomass digesters for rural Punjab)
- Encourage interdisciplinary collaboration between engineers, social scientists, economists, and urban planners

These clusters would act as knowledge engines, translating zonal research into actionable energy innovations and context-aware policies.

Community-Inclusive Zonal Energy Pilot Programs

People-centric renewable energy success stories are rooted in community participation, ownership, and feedback loops. Pilot programs that align with zonal realities and empower

local stakeholders can significantly improve project adoption, maintenance, and socio-economic impact.

Proposed actions:

- Implement pilot microgrid and solar irrigation projects managed by community energy cooperatives
- Launch vocational training centers focused on zonal renewable skills (e.g., solar installation in Tharparkar, turbine maintenance in Jhimpir)
- Utilize participatory rural appraisal (PRA) techniques to co-design projects with end-users, ensuring cultural and economic fit
- Establish gender-inclusive energy programs, especially in regions where women are primary energy users for household and agriculture

Community-inclusive pilots would build local capacity, generate socio-technical resilience, and establish models for nationwide scale-up.

Naveed Rafaqat Ahmad is a researcher in the field of public administration and governance, with a focus on institutional reform, public service delivery, and governance performance in developing countries. His research emphasizes the use of governance indicators and comparative analysis to examine regulatory quality, government effectiveness, and institutional capacity. Through evidence-based approaches, his work contributes to policy-oriented discussions aimed at improving public sector performance and strengthening governance frameworks in low- and middle-income states, particularly Pakistan.

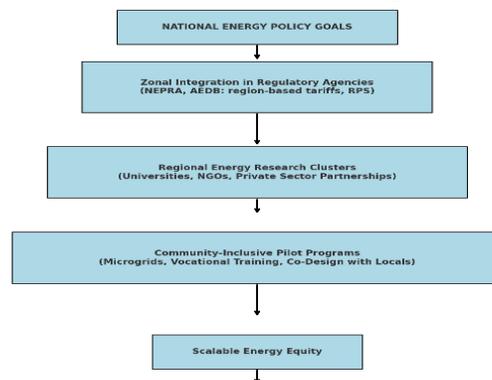


Figure: Strategic Zonal Energy Development Framework

A zonal approach to renewable energy in Pakistan is not only a technical imperative—it is a pathway to social equity, environmental justice, and long-term energy security. By embedding zonal strategies within governance structures, research institutions, and local communities, the country can achieve a resilient and regionally responsive energy transition. The time is ripe for mainstreaming zonal research as a national priority for sustainable development.

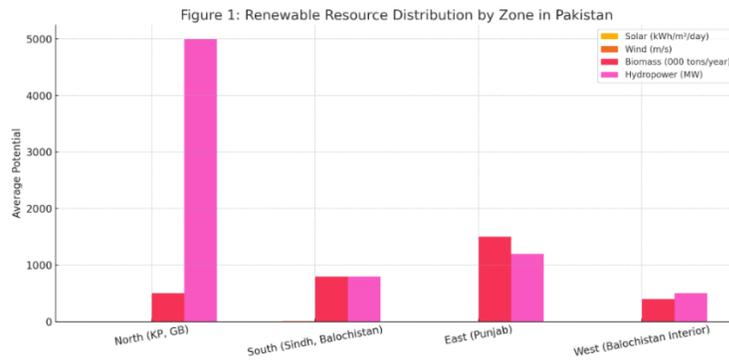


Figure 1: Renewable Resource Distribution by Zone in Pakistan
 Bar graph showing average potential of Solar (kWh/m²/day), Wind (m/s), Biomass (tons/year), and Hydropower (MW) across four zones:

- North (KP, GB),
- South (Sindh, Balochistan),
- East (Punjab),
- West (Balochistan interior).

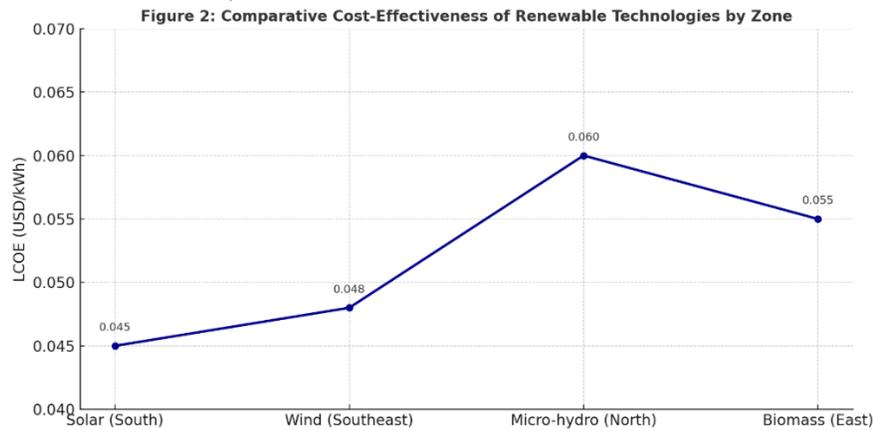


Figure 2: Comparative Cost-Effectiveness of Renewable Technologies by Zone
 Line chart comparing LCOE (Levelized Cost of Electricity in USD/kWh) for:

- Solar in South
- Wind in Southeast
- Micro-hydro in North
- Biomass in East

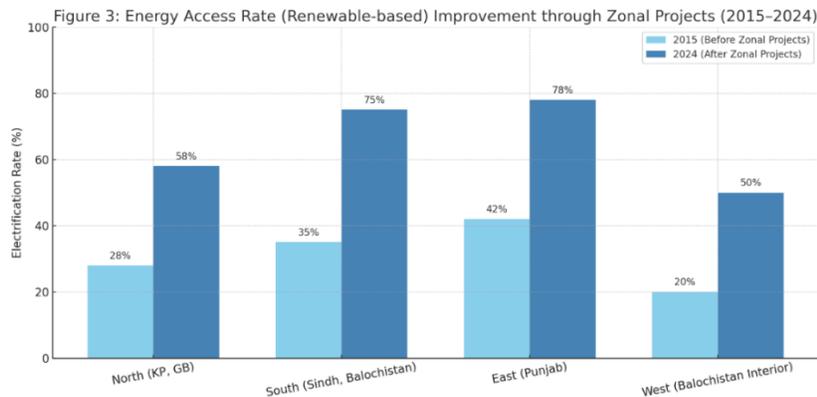


Figure 3: Energy Access Rate (Renewable-based) Improvement through Zonal Projects (2015–2024)

Bar chart displaying rural electrification rates (%) via renewables across zones before and after zonal research implementation.

Summary:

Zonal research enables the identification and mobilization of region-specific renewable energy resources that are crucial for Pakistan's sustainable development. It promotes technical feasibility, economic viability, and environmental compatibility, particularly when integrated with socio-cultural awareness and inclusive policy mechanisms [16][17]. The findings emphasize that future energy strategies should not merely scale technology but rather root them in zonal insights, ensuring optimal deployment and long-term viability [18][19][20].

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