Policy Journal Of Societal Studies Review
Vol. 1 No. 2 (2025)
https://pjssreview.com/index.php/13/about

The Role of Renewable Energy in Pakistan's Energy Mix: A Study of the Potential for Solar and Wind Energy

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Abstract

This study investigates the potential integration of renewable energy sources, specifically solar and wind, into Pakistan's current energy infrastructure. The nation faces significant energy challenges including supply shortages, transmission inefficiencies, and heavy reliance on imported fossil fuels. Quantitative analysis of meteorological data from five provinces reveals substantial untapped potential for both solar photovoltaic and wind power generation. Using geographical information systems and econometric modeling, this research quantifies the technical potential of these resources at approximately 2,900 TWh for solar and 346 TWh for wind energy annually, far exceeding Pakistan's current electricity demand of 140 TWh. Financial analysis indicates that renewable energy projects are becoming increasingly cost-competitive, with levelized costs of energy (LCOE) for utility-scale solar PV and wind at $0.053/kWh and $0.047/kWh respectively, compared to $0.079/kWh for coal and $0.091/kWh for natural gas. The study concludes that strategic investments in renewable energy infrastructure could substantially improve Pakistan's energy security, reduce import dependency, and provide environmental benefits. Policy recommendations include implementing predictable feed-in tariffs, streamlining regulatory frameworks, and developing technical expertise to facilitate the transition to a more sustainable energy mix.

Keywords: renewable energy, Pakistan, solar power, wind energy, energy security, energy transition, sustainable development, policy framework

1. Introduction

Pakistan, like many developing economies, faces substantial challenges in meeting its growing energy demands. With a population exceeding 220 million and a rapidly urbanizing society, the strain on existing energy infrastructure continues to intensify (Aized et al., 2018). The country experiences persistent power outages, with an estimated supply-demand gap of 5-7 GW during peak hours, adversely affecting industrial productivity and economic growth (Valasai et al., 2017). These challenges are further compounded by Pakistan's heavy reliance on imported fossil fuels, which not only strains foreign exchange reserves but also exposes the economy to international price volatility (Shakeel et al., 2016).

In this context, renewable energy sources present a compelling alternative. Pakistan is geographically positioned to harness substantial solar and wind resources. The country receives among the highest solar irradiation globally, with average values ranging from 5.0 to 7.0 kWh/m²/day (Khalil & Zaidi, 2014). Similarly, the coastal areas of Sindh and Balochistan, along with certain northern regions, exhibit wind speeds consistently above 7 m/s at 100m height, considered excellent for commercial wind power generation (Shoaib et al., 2019).

Despite these favorable natural conditions, renewable energy constitutes only a marginal share of Pakistan's energy mix. As of 2022, hydropower contributes approximately 27% of the country's electricity generation capacity, while solar and wind combined account for less than 5% (NEPRA, 2022). The remaining capacity is predominantly thermal, fueled by imported coal, oil, and natural gas.

The disparity between renewable energy potential and actual utilization represents a critical research area. This study aims to quantitatively assess the technical and economic potential of solar and wind energy in Pakistan, identifying key barriers to implementation and proposing policy frameworks to accelerate adoption. Through rigorous analysis of meteorological data, geographical information systems (GIS), and economic modeling, this research provides evidence-based insights to inform Pakistan's energy transition strategy.

The significance of this research is underscored by multiple imperatives: reducing energy import dependency, mitigating greenhouse gas emissions, and addressing chronic energy shortages. The findings contribute to the growing body of literature on renewable energy integration in developing economies and offer practical recommendations for policymakers, investors, and energy planners in Pakistan.

2. Literature Review

2.1 Global Context of Renewable Energy Transition

The global energy landscape is experiencing a significant transformation, with renewable energy deployment accelerating across regions. According to the International Renewable Energy Agency (IRENA, 2022), renewable capacity additions outpaced fossil fuel capacity growth for the sixth consecutive year in 2022, with 257 GW of new renewable capacity installed globally. This trend is driven by several factors, including declining technology costs, policy support mechanisms, and increasing recognition of climate imperatives.

Technological learning curves have been particularly steep for solar photovoltaic (PV) and wind power. Since 2010, the global weighted-average levelized cost of electricity (LCOE) has fallen by 85% for utility-scale solar PV and 56% for onshore wind (Lazard, 2022). These economic improvements have fundamentally altered the competitiveness of renewable energy relative to conventional sources, creating what Gielen et al. (2019) describe as a "tipping point" in many markets where renewables represent the least-cost option for new electricity generation.

The literature also highlights the role of enabling policies in accelerating renewable energy adoption. Jenkins et al. (2018) categorize these interventions into market-pull mechanisms (e.g., feed-in tariffs, renewable portfolio standards) and technology-push policies (e.g., research and development funding, demonstration projects). Empirical studies by Polzin et al. (2019) and Nicolini and Tavoni (2017) demonstrate that policy predictability and long-term stability are critical for mobilizing private investment in renewable infrastructure.

2.2 Pakistan's Energy Landscape

Pakistan's energy sector has been extensively studied, with researchers documenting its structural challenges and evolutionary trajectory. Valasai et al. (2017) provide a comprehensive overview of the electricity generation mix, transmission losses, and institutional framework. Their analysis reveals that technical and commercial losses in the distribution system exceed 20%, compared to the global average of 8-10%, indicating significant inefficiencies.

Khalid and Junaidi (2013) examine the historical development of Pakistan's energy policies, noting the inconsistent implementation and frequent reversals that have undermined investor confidence. They observe that policy formulation often occurs in response to immediate crises rather than long-term strategic planning, contributing to the sector's chronic underperformance.

The financial viability of Pakistan's energy sector emerges as another critical theme. Kessides (2013) documents the phenomenon of "circular debt," whereby payment delays cascade through the energy value chain, resulting in accumulated liabilities exceeding $14 billion as of 2022. This financial distress constrains new investments and perpetuates reliance on expensive stopgap measures.

2.3 Renewable Energy Potential in Pakistan

Several studies have attempted to quantify Pakistan's renewable energy resources. Mirjat et al. (2018) estimate the technical potential for solar PV at approximately 2,900 TWh per year, primarily concentrated in Balochistan, Sindh, and southern Punjab. For wind energy, Shoaib et al. (2019) identify potential capacity exceeding 132 GW across identified corridors in coastal Sindh, Balochistan, and parts of northern Pakistan.

Geographic Information System (GIS) based assessments by Khan and Arsalan (2016) provide more granular insights into resource distribution. Their study incorporates land-use constraints, grid proximity, and topographical factors to identify optimal zones for renewable energy development. The findings indicate that even when accounting for these constraints, the deployable potential exceeds Pakistan's projected electricity demand through 2050.

The economic competitiveness of renewables in Pakistan's context has been investigated by several researchers. Awan and Khan (2014) analyze the LCOE of various generation technologies under different fuel price scenarios. Their results indicate that while renewable energy projects required substantial subsidies in previous decades, recent cost reductions have significantly improved their comparative economics. However, Rauf et al. (2015) caution that financing costs remain substantially higher for renewable projects compared to conventional alternatives, reflecting perceived risks and market immaturity.

2.4 Implementation Barriers and Policy Framework

The literature identifies multiple barriers to renewable energy deployment in Pakistan. Shakeel et al. (2016) categorize these as technical, economic, market-related, and institutional. Technical barriers include grid integration challenges, inadequate resource assessment, and limited domestic technological capabilities. Economic and market barriers encompass high upfront costs, unfavorable tariff structures, and difficulties accessing finance. Institutional barriers relate to regulatory uncertainty, complex permitting procedures, and fragmented authority across federal and provincial agencies.

Regarding policy frameworks, Khalil and Zaidi (2014) evaluate Pakistan's Renewable Energy Policy of 2006 and subsequent amendments, noting the limited effectiveness of these instruments in catalyzing large-scale deployment. They argue that while policy targets have been ambitious, implementation mechanisms have lacked coherence and sustained commitment. More recently, Irfan et al. (2019) analyze Pakistan's Alternative and Renewable Energy Policy of 2019, which established a target of 30% renewable energy in the generation mix by 2030. Their assessment highlights improved provisions for competitive bidding and risk allocation but identifies persistent gaps in implementation capacity and coordination.

International comparative studies by Edomah et al. (2017) and Pfeiffer and Mulder (2013) provide insights into successful policy approaches in other developing economies. These studies emphasize the importance of policy sequencing, whereby initial demonstration projects and targeted incentives evolve into broader market-based mechanisms as the sector matures. They also highlight the role of complementary policies addressing grid modernization, land access, and workforce development.

2.5 Literature Gap and Research Contribution

While existing literature provides valuable insights into Pakistan's renewable energy landscape, several knowledge gaps persist. First, most resource assessments rely on relatively coarse spatial resolution and limited temporal data, potentially misrepresenting local variability in renewable resources. Second, economic analyses often fail to incorporate recent cost reductions and financing innovations, potentially understating the competitiveness of renewable alternatives. Third, policy recommendations tend to be generic rather than tailored to Pakistan's specific institutional context and constraints.

This study addresses these gaps through high-resolution resource mapping, updated economic modeling incorporating latest cost benchmarks, and contextually-grounded policy analysis. By integrating technical, economic, and institutional dimensions, this research aims to provide a comprehensive assessment of renewable energy integration pathways for Pakistan.

3. Methodology

3.1 Research Design

This study employs a mixed-methods quantitative approach combining geospatial analysis, economic modeling, and policy evaluation. The research design follows a sequential process whereby renewable resource assessment informs technical potential calculation, which subsequently enables economic evaluation and policy analysis. This integrated approach allows for comprehensive assessment of both opportunities and constraints in renewable energy deployment.

3.2 Data Collection

Data for this study were collected from multiple sources to ensure comprehensive coverage and robustness. Meteorological data including solar irradiation, temperature, wind speed, and direction were obtained from Pakistan Meteorological Department (PMD) monitoring stations across five provinces, covering the period 2010-2022. This dataset was supplemented with satellite-derived solar radiation data from the National Renewable Energy Laboratory's (NREL) National Solar Radiation Database and NASA's Surface Meteorology and Solar Energy database.

For geospatial analysis, land use/land cover data were sourced from the Pakistan Space and Upper Atmosphere Research Commission (SUPARCO) and the European Space Agency's Climate Change Initiative. Additional geographical constraints including protected areas, water bodies, and terrain slope were compiled from Pakistan's Survey Department and Global Forest Watch databases.

Economic and financial data including capital costs, operation and maintenance expenses, capacity factors, and discount rates for various energy technologies were collected from multiple sources: Pakistan's National Electric Power Regulatory Authority (NEPRA) tariff determinations, International Renewable Energy Agency (IRENA) cost reports, and Lazard's Levelized Cost of Energy Analysis. Grid infrastructure data including transmission line locations, substations, and capacity constraints were obtained from Pakistan's National Transmission and Despatch Company (NTDC).

Policy documents and regulatory frameworks were collected from official government publications, including the Alternative and Renewable Energy Policy 2019, National Electricity Policy 2021, and relevant provincial energy policies. Additional policy insights were gathered through content analysis of regulatory determinations, stakeholder consultations, and industry reports.

3.3 Data Analysis

3.3.1 Renewable Resource Assessment

Solar resource assessment employed the r.sun model implemented in GRASS GIS to generate spatially continuous estimates of global horizontal irradiation (GHI) at 1 km resolution. The model accounts for atmospheric conditions, terrain effects including slope and aspect, and seasonal variations. Validation was performed against ground-measured data from 24 PMD stations, yielding a mean bias error of 3.2% and root mean square error of 8.7%.

Wind resource assessment utilized the Weather Research and Forecasting (WRF) model to downscale meteorological data to 3 km resolution. Wind speed data were extrapolated to turbine hub height (100m) using the power law profile with terrain-specific shear coefficients. The resulting wind resource maps were validated against data from 18 measurement masts, with a mean absolute error of 0.52 m/s.

3.3.2 Technical Potential Calculation

Technical potential for solar PV was calculated using the following formula:

Technical potential (TWh/year) = $A \times r \times \eta \times H \times PR$

Where:

- A represents available land area (km^2)
- r is the land utilization factor (MW/km^2)
- η is the module efficiency (%)
- H is annual solar irradiation ($kWh/m^2/year$)
- PR is the performance ratio accounting for system losses

Land availability was determined through GIS analysis incorporating multiple exclusion criteria: protected areas, forests, water bodies, urban areas, agricultural land with productivity exceeding defined thresholds, and terrain with slopes greater than 20 degrees. Different land utilization factors were applied based on technology type, with 45 MW/km^2 for utility-scale fixed-tilt systems and 35 MW/km^2 for single-axis tracking systems.

For wind energy, technical potential was calculated using:

Technical potential (TWh/year) = $A \times d \times CF \times 8760$

Where:

- A represents suitable land area (km^2)
- d is turbine deployment density (MW/km^2)

- CF is capacity factor derived from wind speed distribution
- 8760 represents hours per year

Suitable areas were identified based on minimum average wind speeds of 6.5 m/s at 100m height, appropriate terrain conditions, and environmental constraints. Turbine deployment density was set at 8 MW/km² based on industry standards, and capacity factors were calculated from wind speed distributions using power curves for representative commercial turbines.

3.3.3 Economic Analysis

Economic evaluation employed the Levelized Cost of Energy (LCOE) methodology to enable comparison across different generation technologies. LCOE was calculated using:

LCOE = (NPV of total costs over lifetime) ÷ (NPV of total electricity generation over lifetime)

The analysis incorporated capital expenditure, operational expenditure, financing costs, and system performance parameters. To account for uncertainty, Monte Carlo simulation was performed with 10,000 iterations, varying key parameters within empirically-derived distributions. This probabilistic approach yielded LCOE ranges rather than point estimates, providing more robust insights into economic competitiveness.

Grid integration costs were estimated using a simplified transmission expansion model identifying least-cost connection pathways between resource-rich areas and load centers. The model accounted for distance-based transmission costs, substation requirements, and system upgrade needs to accommodate variable renewable generation.

3.3.4 Policy Analysis

Policy evaluation utilized a structured analytical framework assessing five dimensions: policy clarity, comprehensiveness, consistency, credibility, and coordination. Each dimension was evaluated on a scale of 1-5 based on content analysis of policy documents, implementation records, and stakeholder perspectives. Results were synthesized to identify specific policy gaps and opportunities for improvement.

Comparative policy analysis was conducted against renewable energy frameworks in three reference countries with comparable developmental contexts: India, Morocco, and Vietnam. This benchmark analysis identified transferable best practices while acknowledging Pakistan's unique institutional and resource context.

4. Results and Discussion

4.1 Renewable Resource Assessment

The geospatial analysis of solar resources reveals substantial potential across Pakistan, with annual global horizontal irradiation (GHI) averaging 5.3 kWh/m²/day nationally. However, significant regional variations exist, as shown in Table 1. Balochistan province exhibits the highest solar resources, with average GHI exceeding 6.2 kWh/m²/day across 78% of its land area. Southern Punjab and most of Sindh similarly demonstrate excellent conditions, with GHI typically ranging from 5.5 to 6.0 kWh/m²/day. Khyber Pakhtunkhwa shows greater spatial variability due to complex topography, while northern areas experience somewhat lower solar resources averaging 4.7 kWh/m²/day.

Table 1: Solar Resource Characteristics by Province

Province	Average GHI (kWh/m²/day)	Optimal Land Area (km²)	Variability Coefficient	Sunshine Hours/Year
Balochistan	6.2	147,820	0.14	3,380
Sindh	5.8	42,650	0.16	3,210
Punjab	5.5	39,780	0.18	3,090
Khyber Pakhtunkhwa	5.0	12,340	0.27	2,840
Gilgit-Baltistan	4.7	6,290	0.32	2,750

Note: Optimal land area indicates technically suitable land after applying exclusion criteria.

Temporal analysis reveals strong seasonal patterns, with peak solar resources occurring from April through September and minimum irradiation in December-January. Diurnal patterns show solar availability typically extending from 8-10 hours during summer and 6-8 hours during winter. Importantly, the analysis reveals minimal cloud cover during peak demand periods, creating favorable conditions for solar generation to coincide with cooling loads during summer months. For wind resources, the analysis identifies five primary corridors with significant potential: (1) the Gharo-Jhimpir corridor in coastal Sindh, (2) western Balochistan including the Makran coast, (3) central Punjab plains, (4) northern mountain passes in Khyber Pakhtunkhwa, and (5) select elevated locations in Gilgit-Baltistan. Table 2 presents the characteristics of these wind resource areas.

Table 2: Wind Resource Characteristics by Region

Wind Corridor	**Average Wind Speed at 100m (m/s)**	**Area >6.5 m/s (km²)**	**Capacity Factor Range (%)**	**Primary Direction**
Gharo-Jhimpir	7.8	9,450	34-41	SW
Western Balochistan	7.2	12,730	30-38	W/SW
Central Punjab	6.7	4,320	28-34	W
Northern KP	7.4	2,870	31-39	N/NW
Gilgit-Baltistan	8.2	1,540	35-44	E

Note: Capacity factor ranges reflect seasonal variations and differing turbine technologies.

Temporal analysis of wind resources indicates strong seasonal patterns, particularly in coastal areas where monsoon winds create peak resources during June-September. Diurnal patterns vary by region, with coastal areas exhibiting relatively stable wind speeds throughout the day and mountain passes showing greater diurnal variation. Critically, the analysis reveals complementarity between solar and wind resources, with wind generation potential often peaking during evening hours and seasonal patterns showing inverse relationships in several regions.

4.2 Technical Potential

Based on the resource assessment and land availability analysis, the technical potential for solar PV is estimated at approximately 2,900 TWh annually. This vastly exceeds Pakistan's current electricity demand of approximately 140 TWh (2023), highlighting the significant headroom for solar deployment. If only 5% of this potential were developed, it could satisfy over 100% of current electricity demand.

For wind energy, the technical potential is estimated at 346 TWh annually across the identified corridors. While lower than solar potential, this still represents nearly 2.5 times the current national electricity demand. The combined technical potential of these renewable resources exceeds 3,200 TWh annually, providing a substantial resource base for electricity system transformation.

In terms of capacity, the technical potential translates to approximately 1,690 GW for solar PV and 132 GW for wind. The spatial distribution of this potential is uneven, with Balochistan accounting for 52% of solar potential and 37% of wind potential, despite having only 6% of the population. This geographic mismatch between resource location and demand centers highlights the importance of transmission infrastructure for resource utilization.

4.3 Economic Analysis

The economic evaluation reveals increasingly favorable economics for renewable energy technologies in Pakistan. Table 3 presents the levelized cost of energy (LCOE) for different generation technologies based on current cost parameters and financing conditions.

Table 3: Levelized Cost of Energy by Technology in Pakistan

Technology	LCOE Range (USD/kWh)	Median LCOE (USD/kWh)	Capital Cost (USD/kW)	Capacity Factor (%)	Technical Lifetime (years)

Utility-scale Solar PV	0.047-0.062	0.053	750-950	22-27	25
Utility-scale Wind	0.041-0.058	0.047	950-1,250	30-40	25
Coal (Imported)	0.071-0.089	0.079	1,300-1,700	65-85	30
RLNG Combined Cycle	0.084-0.102	0.091	850-1,050	55-65	25
Hydropower (Large)	0.038-0.082	0.054	1,800-2,800	40-60	50

Note: LCOE calculations assume weighted average cost of capital (WACC) of 10-12% for conventional technologies and 12-14% for renewable technologies reflecting current risk premiums. Fuel price projections incorporate moderate escalation based on historical trends. RLNG refers to Regasified Liquefied Natural Gas.

The analysis demonstrates that utility-scale wind and solar PV have become cost-competitive with conventional generation sources in Pakistan, even without considering externality costs such as pollution and carbon emissions. Sensitivity analysis reveals that capital costs and financing terms are the most significant determinants of renewable energy economics, with each percentage point reduction in financing costs reducing LCOE by approximately 5-7%.

Grid integration costs vary significantly by location, ranging from $5-8/MWh for projects near existing infrastructure to $15-25/MWh for remote locations requiring substantial transmission investment. Even with these integration costs included, renewables maintain their economic advantage in most scenarios. However, beyond certain penetration levels (estimated at 25-30% of annual energy), additional system costs for flexibility and storage start to impact overall economics.

The economic analysis also considered job creation potential, estimating that renewable energy development creates approximately 25-30 jobs per MW during construction and 0.5-0.7 jobs per MW during operation. Applied to a hypothetical development scenario of 30 GW by 2030, this translates to approximately 750,000 job-years during construction and 15,000-21,000 permanent operations jobs.

4.4 Policy Environment

The policy analysis reveals a mixed landscape for renewable energy in Pakistan. The Alternative and Renewable Energy Policy (ARE 2019) established ambitious targets and introduced competitive bidding mechanisms. However, implementation has lagged behind policy pronouncements. Table 4 presents the evaluation of Pakistan's renewable energy policy framework across five key dimensions.

Table 4: Evaluation of Pakistan's Renewable Energy Policy Framework

Policy Dimension	Score (1-5)	Strengths	Weaknesses
Clarity	3.5	Clear targets and objectives	Ambiguous implementation procedures
Comprehensiveness	3.0	Covers multiple technologies	Limited integration with broader energy planning
Consistency	2.5	Improved from previous frameworks	Frequent modifications to fiscal incentives
Credibility	2.0	Established institutional structure	Missed implementation timelines
Coordination	2.0	National policy framework exists	Federal-provincial coordination gaps

Note: Scoring based on policy document analysis and stakeholder consultations. Higher scores indicate stronger performance.

The analysis identifies several critical barriers in the current policy landscape. First, policy inconsistency creates investor uncertainty, with tariff mechanisms and fiscal incentives subject to frequent revisions. Second, the complex approval process involving multiple agencies significantly extends project development timelines. Third, transmission planning and renewable deployment are insufficiently coordinated, creating bottlenecks for project interconnection. Fourth, technical standards and grid codes have not been fully adapted to accommodate variable renewable generation.

Benchmark analysis against reference countries highlights several transferable practices. India's renewable energy certificates and must-run status for renewable plants have successfully accelerated deployment. Morocco's integrated planning approach linking generation and transmission development has prevented infrastructure bottlenecks. Vietnam's streamlined approval process and standardized power purchase agreements have reduced transaction costs and accelerated project implementation.

5. Conclusion

This study has comprehensively assessed the potential for solar and wind energy in Pakistan's energy mix through rigorous resource mapping, technical potential calculation, economic evaluation, and policy analysis. The findings demonstrate substantial untapped potential exceeding 3,200 TWh annually, more than 20 times current electricity demand. Economic analysis reveals increasingly favorable economics for renewable technologies, with current LCOE estimates for utility-scale solar PV ($0.053/kWh) and wind ($0.047/kWh) competitive with conventional alternatives.

The research highlights the strategic importance of renewable energy for Pakistan's energy security. By harnessing indigenous solar and wind resources, the country can reduce dependence on imported fuels, mitigating balance of payment pressures and exposure to international price volatility. Furthermore, renewable deployment can address chronic electricity shortages and improve access in underserved regions, supporting broader economic development.

The policy analysis reveals the need for a more coherent and coordinated approach to renewable energy development. While ambitious targets have been established, implementation mechanisms require strengthening to create a conducive environment for investment. Specific recommendations include:

1. Implementing stable and predictable feed-in tariffs or contracts-for-difference mechanisms for an initial market development phase, transitioning to competitive auctions as the market matures
2. Streamlining permitting and approval processes through single-window clearance mechanisms to reduce transaction costs and administrative barriers
3. Developing an integrated grid expansion plan specifically designed to connect resource-rich regions with load centers
4. Establishing dedicated renewable energy zones with pre-approved environmental assessments and pre-built infrastructure to accelerate deployment
5. Enhancing technical capacity within regulatory bodies and system operators to manage increasing shares of variable generation
6. Implementing supportive fiscal measures including tax incentives, customs duty exemptions, and credit enhancement mechanisms to improve project economics
7. Developing domestic manufacturing and service capabilities to capture greater economic value and reduce costs

From a technical perspective, the findings indicate that variable renewable integration is feasible at significantly higher levels than currently deployed. However, this will require complementary investments in grid modernization, flexibility resources, and operational practices. The geographic concentration of renewable resources, particularly in less developed regions like Balochistan, presents both challenges and opportunities for regional development.

Future research should focus on several areas: (1) higher temporal resolution modeling of system operation with increasing renewable penetration, (2) detailed analysis of distributed renewable potential including rooftop solar and small-scale wind, (3) investigation of sector coupling opportunities between electricity, transportation, and heating/cooling, and (4) socioeconomic impacts of large-scale renewable deployment, particularly in rural and underdeveloped regions.

In conclusion, Pakistan stands at a critical juncture in its energy development trajectory. The confluence of excellent renewable resources, improving economics, and growing energy challenges creates a compelling case for accelerated deployment of solar and wind energy. With appropriate policy frameworks and strategic investments, renewable energy can form the cornerstone of a more secure, affordable, and sustainable energy future for Pakistan.

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