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SMART GRID INTEGRATION OF RENEWABLE ENERGY SOURCES FOR SUSTAINABLE POWER SYSTEMS IN PAKISTAN

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Abstract

Pakistan's power sector faces chronic challenges including high transmission and distribution losses (~18%), circular debt, reliance on expensive imported fossil fuels, and an outdated unidirectional grid ill-equipped for modern demands. The rapid, consumer-driven proliferation of distributed solar PV reaching an estimated 5.3 GW of net-metered capacity by March 2025 and potentially 20–22 GW total distributed solar has triggered reverse power flows, threatening local network stability and necessitating a transition to smart grid infrastructure. This review examines the technical, policy, and economic dimensions of integrating variable renewable energy (primarily solar and wind) into Pakistan's grid through smart grid technologies. Pakistan possesses abundant renewable resources, with solar technical potential exceeding 100,000 MW (concentrated in Balochistan and Sindh) and significant wind corridors along the southern coast offering capacity factors of 32–35%. Key smart grid enablers include Advanced Metering Infrastructure (AMI) rollouts, enhanced SCADA with Phasor Measurement Units, HVDC transmission, Battery Energy Storage Systems (BESS), and AI/ML-based forecasting and optimization. Policy frameworks such as the Alternative and Renewable Energy Policy 2019, the Indicative Generation Capacity Expansion Plan (IGCEP) 2024–2034, and the Competitive Trading Bilateral Contracts Market (CTBCM) aim to achieve 30% renewable share (excluding large hydro) by 2030 and an 87% indigenization ratio. Despite declining levelized costs of electricity (LCOE) for utility-scale solar (27–45 USD/MWh by 2030) and wind, persistent barriers technical (outdated infrastructure), financial (high upfront costs), institutional (state monopoly legacy), and regulatory continue to slow deployment. The paper concludes that coordinated deployment of smart grid technologies, energy storage, market reforms, and international partnerships offers a viable pathway to a resilient, sustainable, and cost-competitive power system in Pakistan.

INTRODUCTION

The global energy landscape is currently navigating a period of profound structural change, characterized by the dual imperatives of decarbonization and the enhancement of grid reliability through technological innovation (Marques, 2025). For Pakistan, this transition is not merely a theoretical pursuit of environmental stewardship but a critical response to a persistent energy crisis that has constrained its economic growth for decades (CDM Smith, 2025). The

traditional power grid in Pakistan, originally architected for centralized thermal generation and unidirectional power flows, has become increasingly ill-suited to manage the dynamic requirements of a modern, digitized economy (Awad et al., 2026). The integration of variable renewable energy (VRE) sources primarily solar and wind into the national grid represents the most viable pathway toward achieving energy security, economic stability, and environmental sustainability (Ahmed & Mahmood, 2019). However, this shift necessitates a fundamental transformation of the electrical infrastructure into a "Smart Grid" (SG), a sophisticated system that utilizes digital communication technologies and advanced automation to optimize the production, distribution, and consumption of electricity (Al-Ammar et al., 2025).

2. The Contemporary Power Sector Paradigm in Pakistan

Pakistan's power sector has historically been defined by a centralized single-buyer model, where the federal government, through the Central Power Purchasing Agency (CPPA), manages long-term power purchase agreements with various generators (Zulfiqar et al., 2022). This model, while providing some stability in the early 1990s, has led to significant structural weaknesses, including the accumulation of "circular debt" a financial shortfall resulting from high generation costs, transmission losses, and inadequate revenue recovery (Bacon, 2019). As of 2024, the sector faces an annual financial loss of approximately Rs 265 billion due to transmission and distribution (T&D) losses, which currently stand at roughly 18% of the total power supply (Profit by Pakistan Today, 2026). These losses, combined with a heavy reliance on expensive imported fossil fuels such as Liquefied Natural Gas (RLNG) and Residual Fuel Oil (RFO), have resulted in skyrocketing electricity tariffs for consumers, nearly doubling in the period between 2021 and 2024 (Mehmood, 2025).

The resulting economic pressure has catalyzed a consumer-led "solar boom," where households and industries are increasingly opting for distributed energy resources (DERs) to bypass the national grid (Institute for Energy Economics and Financial Analysis, 2025). This rapid, often unplanned adoption of rooftop solar systems has introduced new technical challenges for grid operators, as high daytime reverse power flows threaten to destabilize local distribution networks (GIZ, 2025a). The transition to a smart grid is therefore an urgent technical requirement to manage these bidirectional flows and maintain system frequency within permissible limits (Al-Ammar et al., 2025).

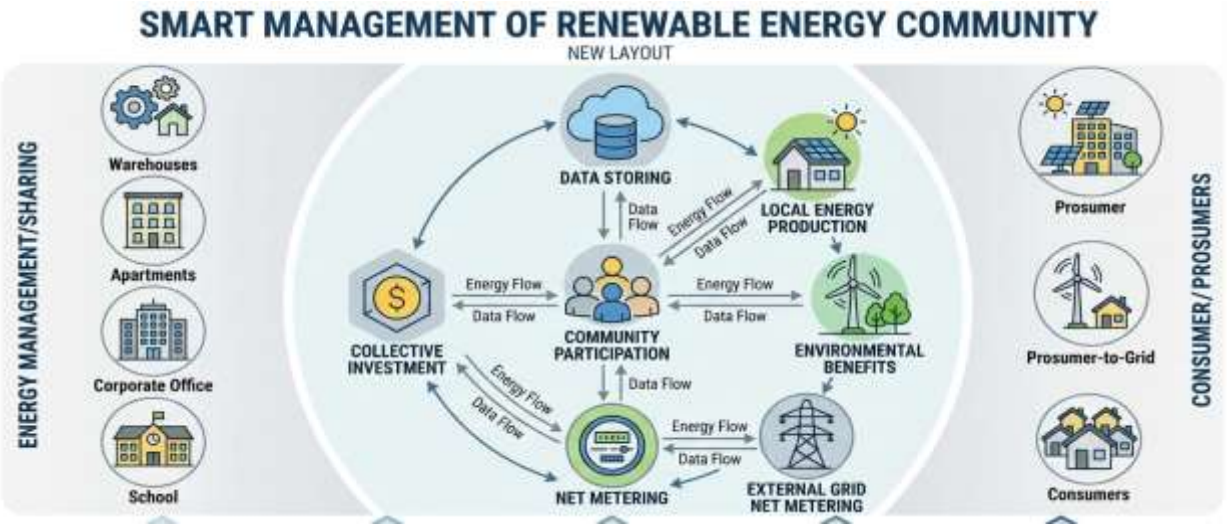


Figure 1: Multidimensional Model for Smart Management of Renewable Energy Communities and Prosumer Integration.

2.1 Current Electricity Generation and Installed Capacity Profiles

As of the end of the 2023-2024 fiscal year, the country's total installed capacity stood at approximately 45,123.9 MW, excluding certain captive power plants and net-metering installations (National Electric Power Regulatory Authority, 2024a).

Table 1: Pakistan's Installed Capacity and Generation Mix (FY 2023-2024)

Technology Category	Installed Capacity (MW)	Percentage Share (%)	Generation Contribution (GWh)
Thermal (Fossil Fuels)	27,847.6	62%	58,000 - 80,000
Hydropower	10,648.6	24%	42,918 - 46,889
Nuclear	3,620.0	8%	15,000 - 18,000
Renewable (Wind, Solar, Bagasse)	3,007.7	6%	5,600 - 6,500
Net-Metered Solar (Est. Mar 2025)	5,300.0	N/A	Variable (Self-consumed)

Analysis of the generation mix reveals that while thermal power remains the dominant source, its share has seen a gradual decline as the system operator prioritizes least-cost dispatch from hydropower and nuclear units (Muhammadi et al., 2024). Hydropower generation bridges the gap during summer and shoulder months, which are transitional periods characterized by moderate demand and increased water availability (Wasti et al., 2022).

2.2 The Impact of Distributed Solar PV and Net Metering

By March 2025, net-metered solar capacity reached approximately 5.3 GW, up from 1.3 GW just two years prior. Total distributed solar generation capacity in the country may range between 20,000 and 22,000 MW (Alghanem, 2025). This shift has profound implications for grid demand; total electricity sales to the national grid fell by 3% in 2024 (Jäger-Waldau, 2019).

3. Technical Potential and Geographic Suitability of Renewable Resources

Pakistan is endowed with immense renewable energy potential, particularly in its southern and western regions (Mordor Intelligence, 2025).

3.1 Solar Energy Resource Assessment

Pakistan is located within the "Sunny Belt," where global average solar radiation ranges from 5 to 7 kWh/m2/day. The technical potential for solar power generation is estimated at over 100,000 MW (International Trade Administration, 2025).

Table 2: Solar Energy Technical Potential by Province

Region/Province	Average Radiation (kWh/m2/day)	Annual Sunshine Hours	Technical Potential (MW)
Balochistan	5.9 - 6.2	2,700 - 3,000	1,200,000 (WB Estimate)
Sindh (South-East)	5.3 - 5.5	2,300 - 2,700	50,000+
Punjab (Deserts)	5.0 - 5.3	2,000 - 2,400	40,000+
Northern Regions	< 4.5	< 2,000	Limited (distributed only)

3.2 Wind Energy Resource Assessment

Pakistan's wind energy potential is primarily concentrated along a 1,100 km coastal belt. The power available from wind is generally calculated using the equation:

$$P = 0.5 \times C_p \times \rho \times A \times v^3$$

where $P$is the power output, $C_p$is the power coefficient, $\rho$is the air density, $A$is the swept area of the turbine blades, and $v$is the wind speed. High wind velocities in the Sindh wind corridor, typically ranging from 6 to 7.5 m/s, result in capacity factors of approximately 32% to 35% (Khan, 2023).

Table 3: Pakistan's Wind Corridor Potential and Current Generation

Wind Corridor	Location	Exploit. Potential (MW)	Current Generation (MW)	Wind Speed (m/s)
Gharo-Jhimpir	Sindh	11,000	1,845	7.0 - 8.0
Coastal Belt	Sindh/Balochistan	50,000	Negligible	6.0 - 7.5
Chaghi/Makran	W. Balochistan	20,000	0	6.5 - 7.5
Northern Passes	KPK/Gilgit	3,000	0	Variable

4. Smart Grid Architecture and Technological Enablers

The integration of intermittent RES necessitates a fundamental shift to an "active" network (Raza et al., 2022).

4.1 Advanced Metering Infrastructure (AMI) and Demand-Side Management

Current government plans involve a large-scale AMI rollout across five major DISCOs Lahore (LESCO), Multan (MEPCO), Peshawar (PESCO), Hazara (HAZECO), and Quetta (QESCO). Field implementation at GEPCO has already demonstrated that smart metering can identify low power factor situations (Field implementation and case study at GEPCO, 2025).

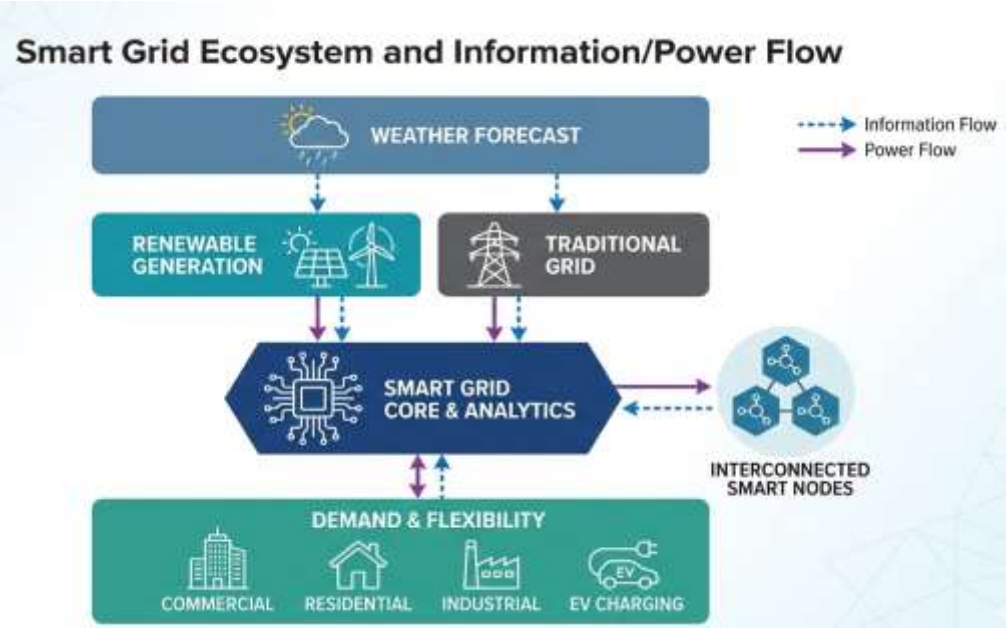


Figure 2: Conceptual Framework of Smart Grid Ecosystems Integrating Bidirectional Power and Information Flows.

4.2 Supervisory Control and Data Acquisition (SCADA) and Wide Area Monitoring

SCADA systems have been utilized since 1992, but the current requirement is for a more granular system utilizing Phasor Measurement Units (PMUs) for high-resolution data on 220 kV and 500 kV transmission lines (Raghunandan, 2022).

4.3 High-Voltage Direct Current (HVDC) Systems

The +660kV Matiari-Lahore HVDC transmission line is superior to traditional AC for long-distance power transfer, eliminating the need for reactive power compensation (Government of Pakistan, 2024).

4.4 Artificial Intelligence and Machine Learning in Grid Optimization

Machine learning (ML) algorithms are being developed for short-term load forecasting, voltage control, and fault detection (Marques, 2025).

5. Policy, Regulatory, and Institutional Frameworks

5.1 Alternative and Renewable Energy (ARE) Policy 2019

The ARE Policy 2019 shifts from "cost-plus" tariffs toward competitive bidding, targeting 30% renewable energy capacity (excluding hydro) by 2030 (Climate Change Laws of the World, 2019).

5.2 Indicative Generation Capacity Expansion Plan (IGCEP) 2024-2034

The IGCEP determines the "least-cost" path for capacity addition over a 10-year horizon (National Electric Power Regulatory Authority, 2024b).

Table 4: Key Metrics for IGCEP 2024-2034 Base Case

Planning Metric	IGCEP 2024-2034 Base Case (FY 2034)	Rationale
Hydropower Target	21,485 MW	Utilize indigenous, stable, low-cost water resources.
Solar PV (Utility)	5,539 MWp	Optimized based on grid stability and load profiles.
Wind Target	1,942 MW	Conservative target due to transmission bottlenecks.
Bagasse/Biomass	1,130 MW	Support rural electrification and agricultural waste usage.
Indigenization Ratio	87.13%	Goal: Reduce reliance on imported coal and LNG.

5.3 The Competitive Trading Bilateral Contracts Market (CTBCM)

The CTBCM model enables direct contracting between producers and Bulk Power Consumers (BPCs), reducing circular debt and rewarding flexible generation (Mukhtar, 2023).

6. Barriers to Smart Grid Integration and Renewable Deployment

6.1 The ISM Hierarchical Barrier Model

Research identifying Pakistan-specific smart grid implementation barriers suggests a five-level hierarchy:

- **Level 5 (Root Drivers):** State monopoly and lack of public awareness (Rehman et al., 2025).
- **Level 4:** Lack of relevant regulations and policies
- **Level 3:** Organizational barriers
- **Level 2:** Economic uncertainty and financial constraints
- **Level 1 (Technical Outcomes):** Outdated grid infrastructure and lack of technical human resources (Raza et al., 2024).

7. Role of Energy Storage and Grid Flexibility

Battery Energy Storage Systems (BESS) are critical enablers for grid flexibility (GIZ, 2025b).

7.1 The BESS Market Boom

Pakistan imported approximately 1.25 GWh of BESS capacity in 2024 (Institute for Energy Economics and Financial Analysis, 2025).

Table 5: Economic Analysis of BESS Across Various Sectors

BESS Sector	Payback Period (Years)	Key Driver
Residential	3 - 5	Lowering energy bills; nighttime backup for solar owners.
Commercial	4 - 6	Peak shaving during high tariff periods.
Industrial	4 - 6	Power quality improvement; avoiding PF penalties.
Utility-Scale	To be determined	Grid stabilization; frequency regulation; black start.

8. International Cooperation and Strategic Partnerships

8.1 CPEC Phase II: The Green and Innovation Corridors

CPEC Phase II focuses on industrial relocation, renewable energy manufacturing, and AI skill development (Iqbal, 2025).

8.2 USAID Power Sector Improvement Activity (PSIA)

USAID has partnered on a $23.5 million project to rehabilitate dams and support market reform through CTBCM implementation (Isaad & Shah, 2025).

9. Economic Viability: Levelized Cost of Electricity (LCOE) Comparison

The fundamental driver for renewable integration is the rapidly declining cost of generation (Muhammadi et al., 2024).

Table 6: LCOE Comparison of Generation Technologies (2024-2030)

Energy Source	LCOE 2024-2025 (USD/MWh)	Projected LCOE 2030 (USD/MWh)	Emissions (gCO2eq/kWh)
Utility-Scale Solar	37 - 60	27 - 45	45
Onshore Wind	37 - 55	30 - 45	11
Solar + 4hr BESS	95 - 120	60 - 85	50
Natural Gas/LNG	85 - 110	Variable (Fuel-led)	490
Imported Coal	75 - 100	Variable (Fuel-led)	820

10. Future Roadmap for Sustainable Power Systems

- **Phase 1 (2025–2027):** Complete AMI installation and finalize BESS regulations
- **Phase 2 (2028–2031):** Full CTBCM implementation and deployment of hybrid wind-solar projects
- **Phase 3 (2032–2034):** Regional interconnectivity and AI-driven governance of distributed energy assets (Wasti et al., 2022).

11. Conclusion

The integration of renewable energy sources into Pakistan's power system through smart grid technologies is no longer an optional strategy but an imperative for resolving the country's longstanding energy crisis, reducing dependence on costly imported fuels, alleviating circular debt, and achieving climate and economic resilience. Abundant solar and wind resources, combined with rapidly falling LCOE for renewables and the

proven technical maturity of smart grid components (AMI, SCADA/PMUs, HVDC, BESS, AI-driven control), provide a strong foundation for transformation. The explosive growth of distributed solar PV already reshaping load profiles and creating reverse power flow challenges underscores both the urgency and the opportunity: unmanaged DER proliferation risks grid instability, while intelligently integrated DERs can enhance flexibility, defer costly transmission upgrades, and lower system costs. Current policy instruments (ARE Policy 2019, IGCEP 2024–34, CTBCM) and international support (CPEC Phase II green corridor, USAID PSIA) offer critical momentum, yet success hinges on overcoming entrenched barriers: modernizing aging infrastructure, building technical and institutional capacity, ensuring predictable and bankable regulatory frameworks, scaling BESS deployment for intermittency management, and accelerating AMI rollout to enable demand-side participation and loss reduction. A phased roadmap beginning with metering and storage regulation (2025–2027), advancing to full market reform and hybrid projects (2028–2031), and culminating in AI-governed, regionally interconnected systems (2032–2034) can deliver a secure, affordable, low-carbon power supply that supports sustainable economic growth. With decisive implementation, Pakistan has the potential to transition from an energy-constrained economy to a renewable-powered, digitally intelligent power system that serves as a model for other developing nations facing similar trilemmas of access, affordability, and sustainability.

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