

A COMPREHENSIVE REVIEW OF SMART GRID AND RENEWABLE ENERGY INTEGRATION IN PAKISTAN

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DOI: <https://doi.org/10.5281/zenodo.20541368>

Keywords

Smart grid; renewable energy integration; Pakistan; smart meters; microgrids; energy storage; grid modernization; electricity reliability; distributed energy resources.

Article History

Received: 07 April 2026

Accepted: 19 May 2026

Published: 04 June 2026

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Abstract

This review examines smart grid development and renewable energy integration in Pakistan, with particular attention to Sindh. It discusses how smart meters, IoT-based monitoring, demand-side management, microgrids, storage systems, HVDC transmission, and digital communication can improve grid reliability and support renewable energy growth. The paper also highlights major barriers, including ageing infrastructure, high transmission and distribution losses, electricity theft, financial constraints, cybersecurity risks, climate-related disruptions, limited storage capacity, and shortage of skilled workforce. In addition, the review considers future directions for Pakistan's power sector, including automated grid control systems, artificial intelligence (AI)-based energy management, predictive maintenance, smart fault detection, advanced cybersecurity protection, and real-time data analytics for improving grid stability and operational efficiency. Future development may also involve wider smart meter deployment, stronger renewable energy forecasting, intelligent load balancing, climate-resilient infrastructure, and better coordination between government agencies, regulators, utilities, and consumers. Overall, the review suggests that Pakistan needs a coordinated smart grid strategy supported by investment, regulation, technical training, public awareness, and stronger institutional planning to build a more reliable, flexible, secure, and renewable-ready power system.

1. INTRODUCTION

Pakistan's electricity sector is moving through a difficult but important transition. For many years, the country has faced issues such as power shortages, high distribution losses, weak recovery, transmission constraints, and rising demand for

reliable electricity. The Government of Pakistan's National Electricity Policy 2021 highlights that reliable, secure, efficient, and affordable electricity is essential for sustainable economic growth, while also recognising that past electricity shortfalls have affected the country's socio-economic

development. In this context, smart grid development is not only a technical improvement but also a necessary step toward a more stable, efficient, and consumer-focused power system. A smart grid uses digital monitoring, communication, automation, sensors, actuators, smart meters, and control systems to improve the flow of electricity and information across the power network. According to the International Energy Agency, smart grids coordinate generators, grid operators, consumers, and electricity market stakeholders so that the system can operate more efficiently while improving reliability, resilience, flexibility, and stability. For Pakistan, this is particularly relevant because the power system includes multiple actors, such as generation companies, transmission companies, distribution companies, independent power producers, consumers, and policy institutions. Better communication between these actors may help reduce technical inefficiencies, improve real-time decision-making, and support faster response to faults and demand changes.

Pakistan's current position is best described as preparatory rather than fully deployed. The literature states clearly that the smart grid is "not in full operation" in Pakistan, even though renewable energy generation is already being used in practice and policy steps have started to support smarter grid functions[1]. One concrete move was NEPRA's issuance of smart meter and tariff guidelines in 2015, which gave a regulatory base for more advanced metering and for consumer-side participation in the power system[2]. This means the country has some of the policy building blocks for a smarter grid, but not yet the broad technical and operational system that would make smart grid capabilities common across the network. The policy landscape has also widened beyond metering. Recent work notes that Pakistan introduced the Energy Wheeling Policy, Energy Import Policy, Net Metering/Distributed Generation Policy, and the Energy Efficiency and Conservation Act as part of a broader effort to manage electricity demand and support a more modern energy market[3]. Together, these policies point to a gradual institutional shift: the state is not only trying to add supply, but also to enable

distributed generation, efficiency, market transactions, and better information flows. In practical terms, net metering is especially important because it lets consumers sell surplus power back to the grid, with smart meters recording both imported and exported electricity and billing only the net. This is a meaningful step toward a more active consumer role, even if the wider grid remains largely conventional. At the institutional level, the literature suggests that Pakistan's smart grid agenda sits between energy regulation, infrastructure planning, and broader development strategy. Ul-Haq et al. argue that the existing grid is poorly suited for decentralization, digitalization, and higher renewable penetration, and they frame smart grid conversion as both a technical and policy task rather than just an engineering upgrade. The same study links this transition to the China-Pakistan Economic Corridor, presenting CPEC as a major opening for investment in grid modernization and as a possible umbrella for power sector transformation[4]. So, institutionally, smart grids in Pakistan are tied not only to utilities and the regulator, but also to national infrastructure planning and external investment channels. Still, the policy direction is ahead of implementation capacity. Soomro et al. (2026) note that smart grid integration is hard because Pakistan's transmission network is unreliable, and because distributed energy sources must meet compatible phase and voltage conditions before they can be synchronized with the main grid[5]. Ul-Haq et al. add that interoperability problems in the current grid create another barrier to a smooth move toward a decentralized and digital system[4]. Taken together, these studies show a common pattern: Pakistan has begun to build a regulatory and institutional foundation for smart grids, but the actual system remains constrained by weak network infrastructure, technical compatibility issues, and the need for coordinated investment and implementation across agencies and utilities. Renewable energy integration is another major reason why Pakistan needs a stronger smart grid framework. The Alternative and Renewable Energy Policy 2019 states that Pakistan has significant renewable energy potential and sets

targets of at least 20% generation capacity from alternative and renewable energy technologies by 2025 and 30% by 2030. The same policy also notes that achieving these targets will require the upgrading of transmission infrastructure. This means that renewable energy cannot be integrated successfully only by installing solar panels or wind turbines. It also requires modern grid communication, flexible control, energy storage, demand-side management, and reliable data systems. The integration of renewable resources creates both opportunities and challenges. Solar and wind energy can reduce dependence on imported fuels and support environmental sustainability, but their output changes with weather and time of day. The IEA explains that higher shares of variable renewable energy require additional measures such as demand response, energy storage, stronger grids, and stability solutions. Therefore, a smart grid communication framework for Pakistan should include both inter-grid communication, which connects larger power networks and control centres, and intra-grid communication, which links local assets such as transformers, substations, smart meters, and consumer-side systems[6].

The proposed framework shown in the figure 1-4 brings these elements together by connecting renewable energy resources, power generation companies, transmission and distribution companies, independent power plants, consumer load management, energy efficiency, and off-site research and policy support. It also reflects the importance of Pakistan's distribution reform agenda, as the World Bank's 2024 Pakistan Development Update focuses specifically on the dynamics of power sector distribution reforms[7]-[10]. Overall, smart grid integration can support Pakistan in building a power system that is more reliable, more flexible, and better prepared for renewable energy growth

The main purpose of this review paper is to examine how smart grid technologies can support renewable energy integration and improve power system reliability in Pakistan, with particular attention to Sindh. The paper reviews the role of inter-grid and intra-grid communication, smart metering, monitoring systems, data acquisition,

energy efficiency, and consumer load management in developing a modern electricity network. It also identifies the major barriers to smart grid implementation, including high transmission and distribution losses, aging infrastructure, electricity theft, financial constraints, cybersecurity risks, climate-related disruptions, limited storage capacity, and shortage of skilled workforce. By reviewing these issues together, the study aims to provide a clear understanding of the opportunities, challenges, and future directions for smart grid development in Pakistan's energy sector.

2. Smart Grid Applications, Technologies and Energy Context

The Pakistani literature presents smart-grid development mainly through targeted case studies rather than large-scale national implementation. These studies focus on areas such as grid-station performance analysis, national transmission planning, utility-scale solar integration, and the use of microgrids in remote or underserved regions. Together, these examples provide practical insights into how smart-grid technologies may support Pakistan's evolving energy system under different operational conditions.

2.1 Applications and Case Studies in Pakistan

2.1.1 132 kV Grid-Station Case Study in Layyah

One applied example comes from a case study at a 132 kV grid station in Layyah, Pakistan, where decentralized generation, advanced control, communication, and web-enabled power-system components are discussed in the context of smart-grid transition. This is useful because it shows smart-grid ideas being tested at an actual grid-station level rather than only in abstract models[11].

2.1.2 National-Grid Planning with NTDC Collaboration

Another important application is at the transmission-planning level. A study on the optimal placement and sizing of FACTS devices was applied to Pakistan's national grid for both the 2018 system and a forecasted 2025 system, and the work was done with the power system planning department of NTDC. The case is tied directly to

Pakistan’s real grid problems: high losses, overloaded lines, and the need to improve power transfer on the transmission backbone linking generators to load centers[10].

2.1.3 Utility-Scale Solar as a Grid-Modernization Use Case

Large renewable plants are another practical part of Pakistan’s smart-grid pathway because they create the need for better forecasting, control, and grid integration. A clear example is the 100 MW Sapphire Solar Power Plant in Chakwal, which has operated since 2018 and is reported to produce about 165 GWh per year. The case shows that large-scale solar is already working in Pakistan and can supply substantial clean power, which strengthens the case for smarter grid operation to absorb more variable renewable energy[9].

2.1.4 Microgrids for Gwadar, Chagai, and Other Remote Areas

A more localized application appears in microgrid test-bed work aimed at places far from the main

grid. One 2024 study reports practical implementation and evaluation of a microgrid control approach in a controlled test-bed and argues that microgrids can provide reliable electricity in remote and rural regions such as Gwadar and Chagai District. The reported value is not only electrification, but also better power sharing among distributed generators, stable operation under changing loads, and support for renewable integration[9], [12].

2.1.5 What These Case Studies Show Overall

Taken together, these applications suggest that Pakistan’s smart-grid progress is happening through incremental, problem-driven deployments: substation and grid-station studies, transmission-planning tools for congestion and losses, large renewable plants that push the grid to modernize, and microgrids for areas the main grid does not serve well.As shown in Figure 1 and 2.

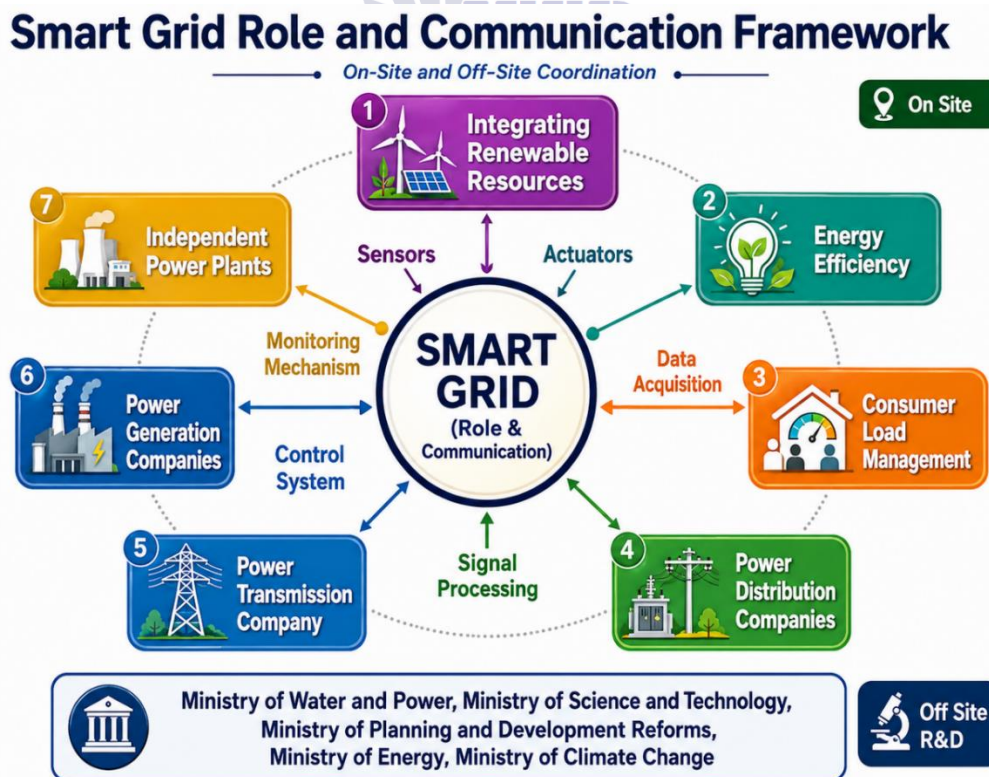


Figure 1: Smart Grid Role and Communication Framework



Figure 2: Smart Grid Communication and Coordination Framework

2.2 Smart Grid Technologies and Architectural Pathways

The literature in Pakistan suggests that smart grid development requires an integrated technological framework rather than a single standalone solution. The main architectural pathways include smart meters, demand-side and load management systems, IoT-based monitoring, microgrids, HVDC transmission links for long-distance renewable energy transfer, and power-quality devices that help households and businesses maintain stable electricity supply during poor grid conditions[7], [8].

2.2.1 Smart Meters as the Base Digital Layer

Several papers treat smart meters as a core entry point for smart grids in Pakistan because they improve measurement, billing, visibility, and theft detection. One study on theft reduction explicitly develops a low-cost smart meter for grid modernization in Pakistan, while another presents a consumer-side smart energy meter as part of a

system spanning substations, distribution, and end users. A recent review also describes smart meters as a foundational ICT element for turning the grid into a smarter and more sustainable system[13]-[15].

2.2.2 Demand-Side Management and Direct Load Control

A major architectural pathway is to manage demand more actively instead of only adding supply. The literature points to load management of air-conditioning demand using ripple-control-like methods, with results suggesting reduced summer peak demand and meaningful energy savings if utilities scale it up. More recent work extends the same logic with IoT-based load control and monitoring to improve conventional load management and reduce load shedding pressure. Residential demand-side management is also discussed in the context of microgrids in southern Pakistan[16].

2.2.3 IoT and ICT for Monitoring, Control, and Grid Visibility

Beyond metering alone, the proposed smart grid architecture in Pakistan often relies on wider ICT integration so utilities can see and manage power flows in near real time. Saleem et al. argue that combining ICT with renewable energy can improve visibility and control in the existing grid, and Ali et al. describe IoT-based load management as a way to monitor and control distribution more effectively than conventional approaches. In simple terms, this is the communications and control layer that lets smarter devices work together across substations, feeders, and consumers[16].

2.2.4 Microgrids for Remote Supply, Resilience, and Distributed Renewables

Microgrids appear as one of the clearest architectural options for Pakistan, especially for remote areas and weak-grid regions. Noor argues that Pakistan should be less dependent on long transmission lines and use DC microgrids powered by renewable energy and storage to electrify villages or village clusters; these systems can either connect to the national grid or operate independently during outages. Habib et al. likewise discuss residential microgrid sizing in southern Pakistan, linking microgrids to smart-grid-style demand-side management. The broader microgrid literature also supports both AC and DC configurations, depending on local needs and constraints[17].

2.2.5 HVDC Plus Local Smart Distribution for Renewable Corridors

Another pathway is a two-level architecture: move bulk renewable electricity over long distances with

high-voltage direct current, then distribute it locally through smart grids and microgrids. Khalid et al. present this as a good fit for Pakistan, where renewable resources are often localized and far from demand centers. This approach is especially relevant if the country wants to connect remote wind, solar, or hydro resources while reducing the limits of a purely conventional AC expansion model[18], [19].

2.2.6 Power-Quality Support at the Consumer Edge

Some work focuses on end-user devices that can make poor grid conditions less damaging. Aftab et al. report that a Smart-UPS can help fix power-quality problems in Pakistan and provide cleaner energy than traditional battery UPS systems. This is not a full smart grid architecture by itself, but it shows an important edge technology that can complement a weak or unstable network, especially in homes and small businesses[20].

2.2.7 A Layered Pathway Fits Pakistan Best

Taken together, the papers suggest a layered build-out: smart meters and consumer devices at the edge; IoT and ICT for monitoring and control; DSM for peak reduction; microgrids for resilience and rural access; and HVDC for moving renewable power over long distances before local smart distribution. This matters because Pakistan's smart grid path is not just about one technology, but about combining modular pieces that solve different grid problems at once[3], [17], [21]. As shown in Figure 3 and 4.

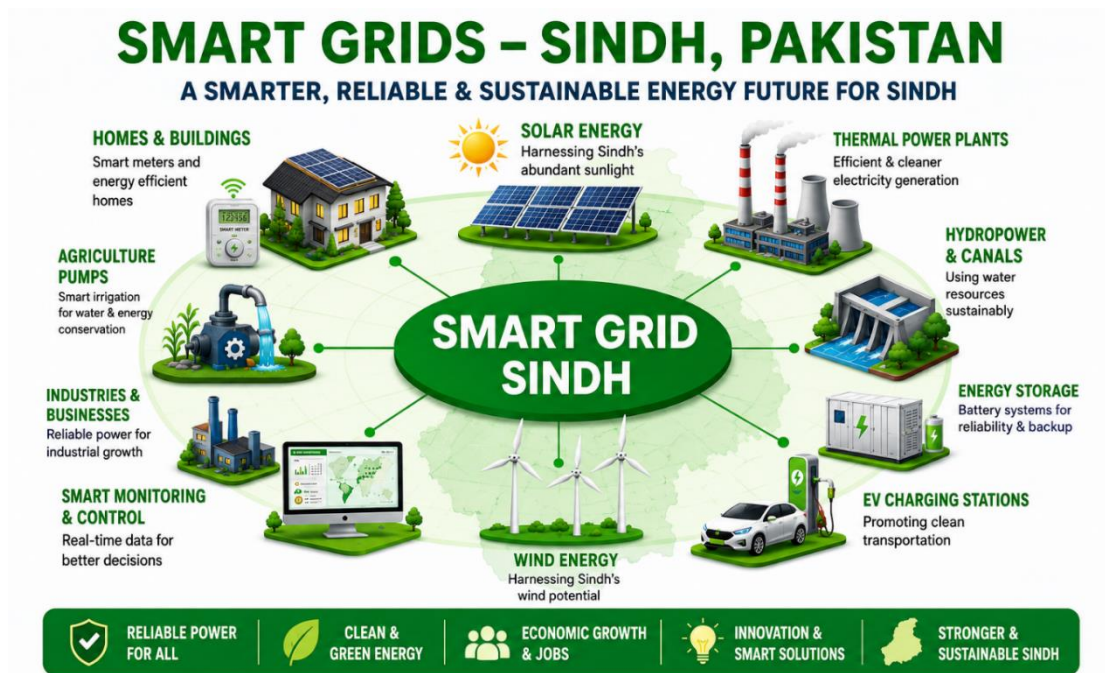


Figure 3: Smart Grid Technologies and Architectural Pathways

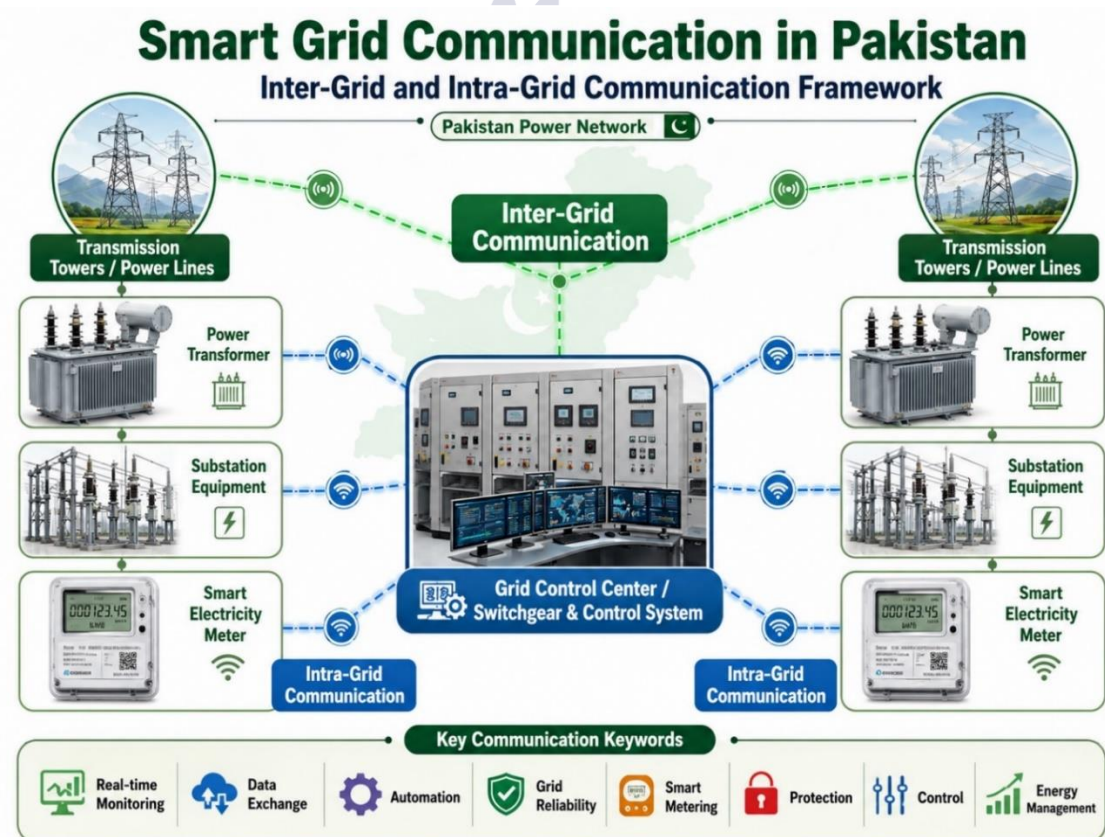


Figure 4: Smart Grids in Sindh, Pakistan

2.3 Pakistan's Energy Crisis and Renewable Imperative

Pakistan faces a persistent power shortfall, rising energy demand, high electricity costs, and frequent load shedding. As a result, renewable energy is no longer only a climate-focused option; it has become a practical solution for improving energy security, reducing dependence on imported fuels, and supporting future smart-grid development. Pakistan's push toward smart grids and renewable integration starts with a basic problem: the country has long faced an electricity crisis marked by a clear

demand-supply gap, rising bills, and frequent outages. One recent review notes that electricity demand was about 120,000 GWh in FY2019–2020 and was expected to rise toward 200,000 GWh by FY2024–2025, while load shedding in some areas can last from a few hours to more than 12 hours per day. The same source links these pressures to weak infrastructure and limited access to reliable power, making power-sector reform central to economic growth and social welfare[22]. As shown in Figure 5 and 6.

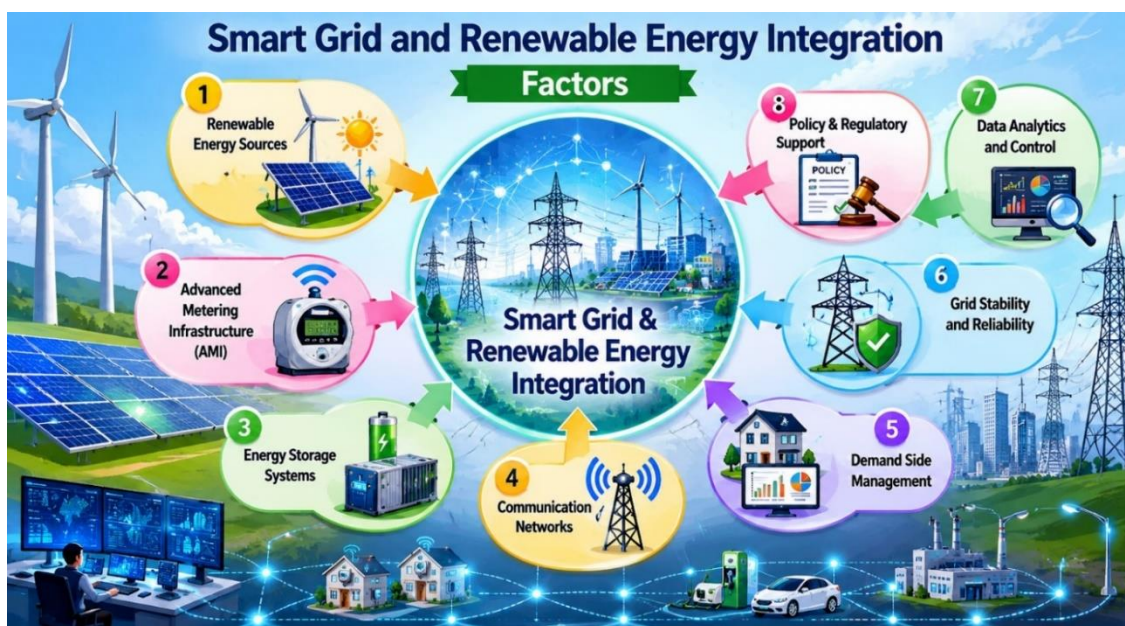


Figure 5: Inter-Grid and Intra-Grid Communication Framework in Pakistan

This crisis also has a strong cost and fuel-security dimension. Studies focused on Pakistan describe a system still heavily shaped by conventional generation, where electricity shortages make central-grid supply expensive and push interest in local renewable and smart-grid options. They argue that stand-alone or hybrid smart-grid models can be attractive in underserved areas because they use local solar and wind resources instead of depending only on an already stressed grid[23]. At the national level, Pakistan's reliance on fossil fuels has also created economic and environmental pressure, strengthening the case for a shift to non-fossil energy sources[24]. Renewables are especially important because Pakistan has

strong natural potential for them. Recent work highlights high solar radiation in the south and strong wind resources along the Sindh and Balochistan coast, making solar and wind a practical response to the energy crisis rather than a purely aspirational one. These resources can help reduce fuel imports, improve energy security, and stabilize long-run electricity costs[25], [26]. This potential is already reflected in the country's progress: Pakistan has expanded solar, wind, and hydropower projects, supported in part by government incentives for private investment. Large solar plants further show that utility-scale renewable deployment is feasible in Pakistan and can reduce dependence on fossil fuels[27]. For this

reason, renewable integration in Pakistan should be seen as both an energy-security strategy and a development strategy. Hybrid renewable systems, especially solar-wind combinations, are presented in the recent literature as a promising way to address supply shortages while also lowering environmental harm and long-term costs. More broadly, studies on smart grids and renewable systems find that greater renewable use can reduce

greenhouse gas emissions, lower fossil-fuel dependence, support energy independence, and create wider economic gains. In short, Pakistan's renewable imperative is driven by three linked facts: demand is rising fast, the current system struggles to deliver affordable and reliable power, and the country has enough renewable resource potential to justify a structural shift [4], [9], [11], [24], [27].

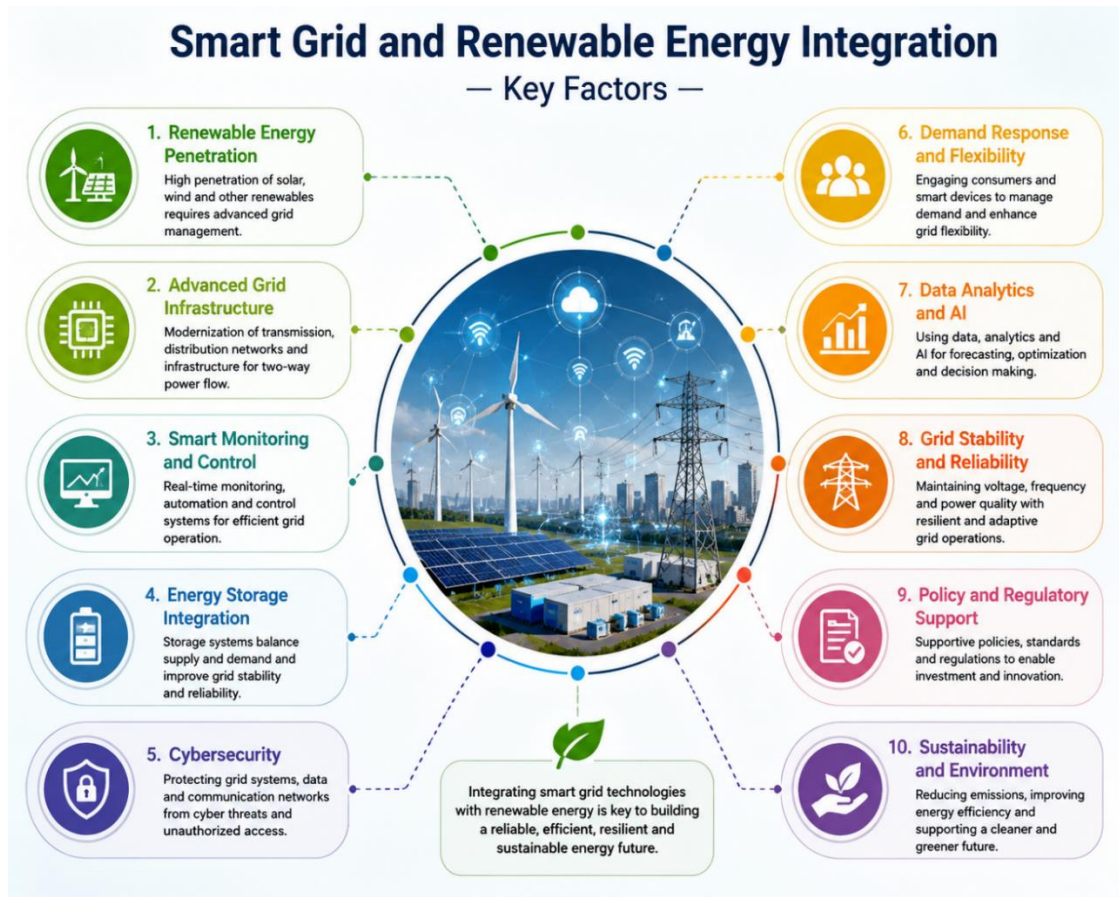


Figure 6: Smart Grid and Renewable Energy Integration Factors

3. Smart Grid Modernization Needs and Challenges

Pakistan's existing electricity grid was originally designed for centralized and conventional power generation. As a result, it is not fully capable of handling large-scale renewable energy integration, increasing electricity demand, or modern two-way power flows. Smart grid modernization can improve system reliability, reduce transmission losses and electricity theft, support net metering

and distributed solar generation, and provide grid operators with better control over a more flexible and efficient power system. Pakistan's grid modernization need follows directly from a structural mismatch: the existing transmission, distribution, and metering system was largely designed for one-way delivery from conventional plants, while the country now needs a system that can handle variable renewable generation, distributed resources, and growing demand.

Multiple studies argue that the present grid cannot adequately bear current load levels, faces interoperability problems, and is ill-suited for decentralization and digitalization, so a major shift toward smart grid architecture is needed [4], [24]. The expected benefits are practical as much as technical. Smart grids can improve demand-supply management, optimize energy flows, strengthen system security, and give consumers a more active role in electricity use. They are also widely presented as a way to cut transmission and distribution losses, improve power quality, and track electricity use more accurately, which matters in Pakistan because theft, weak metering, and poor network performance add to system stress. A second major reason for modernization is renewable integration itself. As Pakistan tries to expand solar and wind, grid operators need more flexibility to manage variability and balance supply with demand. The literature frames this as a core smart-grid function: instead of only adjusting generation, smart grid concepts also manage consumer demand and use digital control to keep the system stable under fluctuating renewable output. This is especially relevant in Pakistan because reliability problems in the existing network can limit smart-grid deployment if the underlying system remains weak. Researchers note that unplanned and forced outages, unreliable transmission, synchronization requirements, and the need for steady voltage from distributed sources all make implementation difficult. That means smart grid rollout is not just about adding software or meters; it also requires physical upgrades to T&D infrastructure, standards compliance, and better grid planning. Modernization also supports a shift from passive consumers to active grid users. Pakistan's 2015 net metering framework already points in this direction by allowing customers with solar PV to use meters that record both imported and exported electricity, encouraging homes and businesses to install their own systems. In practice, this kind of two-way participation works much better in a smart grid than in a conventional grid, because smart control and communication tools give operators better visibility over distributed generation and power flows.

Overall, the case for smart grid modernization in Pakistan is not only that it is desirable, but that it is increasingly necessary. If Pakistan wants to raise the renewable share of electricity while improving service quality, reducing losses, and enabling distributed solar and other new resources, then grid modernization becomes a basic enabling condition rather than a separate reform agenda.

3.1 Key Challenges in Sindh and Pakistan

Aging grid infrastructure means that much of the electricity system, including transmission lines, transformers, substations, and distribution equipment, has become old, overloaded, and less efficient. In Pakistan, and especially in many parts of Sindh, a large part of the power network has been in use for many years without enough upgrading or proper maintenance. Because of this, the system often faces frequent faults, breakdowns, voltage fluctuations, and power interruptions. Old infrastructure also increases technical losses, reduces the ability of the grid to handle growing electricity demand, and makes it more difficult to integrate renewable energy sources such as solar and wind power. In simple words, when the grid is outdated, it cannot support modern, reliable, and efficient electricity delivery. So, this challenge shows that modernization of the grid is necessary to improve power reliability, reduce losses, and support smart grid development in Pakistan. As shown in Figure 7.

3.1.1 High Transmission and Distribution Losses

High transmission and distribution losses refer to the electricity lost while power is carried from generation stations to consumers. In Pakistan, these losses occur due to old wires, overloaded transformers, weak distribution networks, illegal connections, and poor maintenance. These losses reduce the amount of electricity that actually reaches consumers and also increase the financial burden on power distribution companies. For Sindh and Pakistan, this is a major challenge because high losses make the power system inefficient and expensive. Smart grid technologies can help by improving monitoring, detecting faults quickly, identifying theft, and managing electricity flow more effectively.



Figure 7: Key Smart Grid and Power Sector Challenges in Sindh and Pakistan

3.1.2 Aging Grid Infrastructure

Aging grid infrastructure means that many parts of the electricity network, such as transmission lines, transformers, substations, and distribution equipment, are old and overloaded. These outdated systems cannot always handle modern electricity demand, especially in growing cities and industrial areas. This causes frequent breakdowns, voltage fluctuation, power interruptions, and higher technical losses. It also makes renewable energy integration more difficult because solar and wind power require a flexible and modern grid system.

3.1.3 Electricity Theft and Metering Issues

Electricity theft and metering issues are serious problems in Pakistan's power sector. Theft may happen through illegal connections, meter tampering, or unrecorded electricity use. In some areas, outdated meters and weak billing systems also make it difficult to measure actual consumption accurately. This creates financial losses for distribution companies and increases

pressure on honest consumers. Smart meters and automated metering infrastructure can reduce this problem by recording electricity use more accurately and detecting abnormal consumption patterns. Electricity theft occurs when consumers use electricity through illegal connections, meter tampering, bypassing meters, or unregistered supply lines. Metering issues also include old, faulty, or inaccurate meters that cannot properly record actual electricity consumption.

In Sindh and other parts of Pakistan, this problem creates serious financial losses for distribution companies. When electricity is consumed but not paid for, the burden increases on the power sector and honest consumers. It also contributes to higher circular debt, poor revenue recovery, and weak investment in grid improvement. As a result, companies may struggle to upgrade transformers, distribution lines, substations, and smart grid systems[28]. Metering problems also reduce transparency. If electricity consumption is not measured accurately, it becomes difficult to identify where losses are happening. This affects

planning, billing, load management, and demand forecasting. In many cases, manual meter reading can also lead to errors, delays, or manipulation. Smart grid technologies can help reduce these issues through smart meters, automated metering infrastructure, real-time monitoring, and data analytics[29]–[33]. Smart meters can record electricity use more accurately and send data directly to the utility company. They can also help detect unusual consumption patterns, meter tampering, and power theft more quickly. In the context of this review paper, electricity theft and metering issues show why Pakistan needs a more transparent, digital, and automated electricity system. Solving this challenge is important for reducing losses, improving billing accuracy, strengthening revenue recovery, and supporting reliable power supply.

3.1.4 Financial Constraints

Financial constraints refer to the shortage of funds needed to improve, maintain, and modernize Pakistan's electricity system. In the power sector, large investment is required for upgrading transmission lines, replacing old transformers, installing smart meters, developing automated control systems, improving substations, and integrating renewable energy sources. However, many power distribution companies face weak financial conditions, poor bill recovery, high operational costs, and pressure from circular debt. In Pakistan and Sindh, these financial problems make smart grid development difficult[30]–[33]. Even when the need for modern technology is clear, limited funding slows down practical implementation. For example, smart meters, digital monitoring systems, energy storage, and advanced communication networks require high initial investment. If distribution companies do not have enough financial capacity, these projects may remain delayed or only be introduced in limited areas. Financial constraints also affect maintenance. When funds are limited, old grid equipment may not be repaired or replaced on time. This can increase breakdowns, power losses, voltage problems, and unreliable supply. As a result, consumers face poor service, while utility companies lose further revenue. This creates a

cycle where weak finances lead to poor infrastructure, and poor infrastructure causes more losses. For smart grid implementation, strong financial planning is necessary. This may include government support, private investment, international funding, public-private partnerships, and better revenue recovery through smart metering. Without solving financial constraints, Pakistan may struggle to build a reliable, digital, and renewable-ready electricity system.

3.1.5 Climate Change and Extreme Weather

Climate change and extreme weather are important challenges for Pakistan's electricity sector. The power grid is exposed to heatwaves, floods, storms, heavy rainfall, and rising temperatures. These events can damage transmission lines, substations, poles, transformers, and distribution networks. In Sindh, this issue is especially serious because the province often faces intense heat, urban flooding, and climate-related pressure on infrastructure. Extreme heat also increases electricity demand because households, offices, hospitals, and industries need more cooling. When demand rises suddenly, the grid can become overloaded. This may lead to voltage fluctuation, equipment failure, and power outages. Floods and storms can also interrupt electricity supply by damaging physical infrastructure and delaying repair work[30]–[34]. Climate change also affects renewable energy integration. Solar energy production can be affected by dust, high temperatures, and weather variation, while wind energy depends on changing wind patterns. Because renewable energy is naturally variable, the grid must be flexible enough to balance supply and demand. A weak or outdated grid may struggle to manage these changes. Smart grid technologies can help reduce climate-related risks[35], [36]. Real-time monitoring, automated fault detection, weather forecasting, energy storage, and digital control systems can help power companies respond faster during extreme weather events. These technologies can also improve grid resilience, meaning the system can recover more quickly after disruptions.

3.1.6 Cybersecurity Risks

Cybersecurity risks are becoming more important as the electricity system becomes more digital. Smart grids depend on communication networks, sensors, smart meters, control centres, and data systems. While these technologies improve efficiency, they also create risks of hacking, data theft, and cyberattacks. If cyber systems are not protected, attackers could disturb power supply, manipulate data, or damage control systems. Therefore, cybersecurity must be included in smart grid planning from the beginning.

3.1.7 Low Public Awareness

Low public awareness means that many consumers do not fully understand energy conservation, smart meters, electricity theft, renewable energy, or responsible electricity use. Without public understanding, it becomes difficult to implement new technologies and demand-side management programmes. For example, smart meters may face resistance if people do not understand their purpose. Similarly, energy-saving behaviour depends on consumer awareness[37], [38]. Public education is needed to encourage efficient electricity use and support smart grid adoption.

3.1.8 Shortage of Skilled Workforce

A shortage of skilled workforce means there are not enough trained professionals to install, operate, maintain, and manage modern smart grid technologies. Smart grids require knowledge of power systems, communication networks, data analytics, cybersecurity, automation, and renewable energy systems. In Pakistan, traditional grid workers may not always have training in these digital technologies[33], [35], [36]. This skills gap can delay smart grid implementation and reduce system performance. Training programmes, technical education, and industry-academic collaboration are needed.

3.1.9 Load Shedding and Power Reliability Issues

Load shedding and power reliability issues refer to frequent electricity outages, voltage drops, and unstable supply. These problems affect households, businesses, hospitals, schools, and industries. In many areas of Pakistan, unreliable electricity

supply reduces productivity and creates public dissatisfaction. Smart grids can improve reliability by using real-time monitoring, automated fault detection, demand response, and better communication between grid stations. These tools help operators respond faster and manage supply more efficiently.

3.1.10 Limited Energy Storage Capacity

Limited energy storage capacity means that Pakistan does not yet have enough large-scale battery storage or other storage systems to store extra electricity. This is a major challenge for renewable energy integration because solar and wind power are variable. Solar power depends on sunlight, and wind power depends on wind speed[39][40] [39]. Without storage, extra renewable electricity may be wasted during high generation periods, while shortages may occur when renewable output is low. Energy storage can help balance supply and demand, improve grid stability, and support renewable energy growth[41].

4. Renewable Energy Integration and Distributed Energy Models

4.1 Grid Integration Technologies and Operational Mechanisms

In Pakistan, renewable energy integration is not limited to adding solar and wind power plants. It also depends on how electricity is transmitted, balanced, and managed throughout the grid system. The main technologies highlighted in the literature include HVDC transmission for connecting distant renewable energy zones, distributed generation at the distribution level, and advanced control systems such as energy forecasting, active power control, and Automatic Generation Control (AGC) to manage variability, maintain grid stability, and reduce network congestion.

A central technical issue in Pakistan is that much of the best wind and solar resource is far from major load centers, so integration depends on transmission as well as generation. Several studies point to high-voltage direct current, or HVDC, as a useful option for moving large amounts of renewable electricity over long distances with better control than traditional links, especially for

remote wind and solar corridors. This is discussed in the context of linking localized renewable resources to the main grid and strengthening transfer from areas such as Gwadar and Quetta toward demand centers in Sindh and Punjab. In that sense, HVDC is presented not just as a transmission upgrade, but as an integration mechanism that can make large-scale renewable deployment more practical in Pakistan[18], [19]. At the distribution level, the literature shows that renewable integration also depends on how distributed generation is connected and controlled on medium- and low-voltage networks. A Pakistan case study at a 132 kV grid station in Layyah found that adding 24 MW of solar generation to an 11 kV distribution system reduced active and reactive losses, improved voltage profile, and improved power factor. This shows that grid-connected distributed solar can support local network performance when it is properly placed and modeled, rather than being treated only as an extra source of intermittent power. (Mujtaba et al., 2020). But these benefits do not come automatically. Renewable variability can create operational problems such as tripping, unstable voltage, and changing line flows if conventional control remains slow or manual. One Pakistan-focused study notes that renewable integration may cause tripping issues and that conventional control methods are too slow and wasteful for handling them. A more recent study adds that Pakistan still relies on a manual balancing mechanism that overlooks important transmission constraints; under high renewable injection, this can cause major fluctuations in line loading and threaten secure operation. To address this, the authors develop an automatic generation control model for a wind-heavy system to reduce congestion and improve system economics[42]. This points to a broader operational shift: renewable-rich grids need forecasting, automation, and active control, not just more installed capacity. Recent work on smart grids and renewable plants emphasizes the role of data analytics, communication systems, and automation in predicting renewable output, coordinating storage, and shaping demand to keep the grid reliable. In practical terms, this means

operators need tools for active power control, reserve management, and real-time balancing so that wind and solar fluctuations do not simply get pushed onto conventional plants at high cost[43]. Another important mechanism is integration at the consumer end through rooftop PV and net metering, which turns low-voltage feeders into active parts of the grid. However, studies of Karachi's distribution network warn that higher PV penetration can raise feeder voltages and affect losses and transformer loading, especially under changing weather and insolation conditions. This means distribution-system studies, inverter settings, hosting-capacity assessment, and voltage-management strategies are necessary if Pakistan wants to expand prosumer-based solar without creating new local grid problems[44], [45]. Overall, the literature suggests a layered integration model for Pakistan: use stronger long-distance transmission such as HVDC for remote renewable zones, use distributed generation and microgrids for local supply, and use digital control systems to manage balancing, congestion, voltage, and power quality across the network. That combination is what turns renewable potential into usable and reliable electricity on the grid.

4.2 Distributed Energy Resources, Microgrids, Storage, and Prosumer Models

In Pakistan, distributed energy resources can provide practical solutions in areas where the central grid is weak, expensive, or geographically inaccessible. The literature highlights an integrated approach involving rooftop solar systems, battery storage, microgrids, smart net metering, and local energy trading. This combined model can improve electricity reliability, reduce energy costs, and encourage consumers to participate in the power system as active energy producers, often referred to as "prosumers". A key theme in the Pakistan literature is that renewable integration should not be limited to large plants feeding the main grid. Distributed energy resources, especially rooftop PV paired with batteries, can shift part of supply closer to homes and businesses and reduce pressure on the wider system. Studies on smart homes in Pakistan show that rooftop PV and energy storage systems can

reduce residential operating costs, and they frame home-to-grid energy exchange as a useful tool for energy management rather than just self-consumption alone[5], [46], [47]. This matters because it turns households into flexible grid participants that can both use and supply electricity under smart scheduling rules[48]. This leads directly to the prosumer model. As decentralized generation grows in domestic and commercial sectors, Pakistan needs smart metering devices that can measure two-way flows, apply suitable tariffs, and communicate with utilities in real time. One Pakistan study proposes a low-cost smart net-metering device with wireless bi-directional communication for this purpose, showing that prosumer participation depends not only on policy permission but also on practical metering and communication hardware[49]. For areas that are poorly served by the national grid, the literature gives strong support to microgrids and even smaller nanogrids. Earlier work argues that Pakistan should deploy microgrids because they can reduce stress on overloaded transmission and distribution infrastructure, support green energy, and help address the energy crisis. More recent rural case studies extend this idea by proposing hybrid nanogrids and microgrids based on combinations of solar, wind, hydro, biogas, and batteries for communities that are remote, poor, or far from the main network. These systems are presented as especially relevant in rural Pakistan, where long-distance grid extension often brings high transmission and distribution losses. The technical case for microgrids in Pakistan is also becoming more concrete. A recent test-bed study reports that microgrids can manage power distribution effectively in remote areas such as Gwadar and Chagai, maintain voltage and frequency stability under variable conditions, and integrate renewable sources while improving power sharing among distributed generators. The same work finds that an energy management system can raise renewable microgrid capacity by about 20%, suggesting that control and scheduling matter as much as generation hardware[12]. Storage is the main link that makes many of these distributed models workable. The cited studies consistently describe energy storage systems as

important for balancing load and generation, enabling demand response, lowering operating costs, and supporting grid stability, especially when weather or climate conditions are hard on the network. In Pakistan's context, storage therefore serves both local resilience and system-wide flexibility: it helps homes and microgrids use more of their own renewable output, and it helps smooth fluctuations before they become grid problems. Another emerging direction is the move from simple net metering to local energy markets. Recent Pakistan-focused studies propose community energy markets, peer-to-peer trading, and centralized neighborhood smart-grid designs that connect several microgrids or residential systems and optimize exchange between them. These models aim to increase self-sufficiency, improve renewable use, and lower costs and emissions through local trading rather than relying only on the utility as the sole buyer and seller. In this view, the future prosumer in Pakistan is not just a rooftop owner feeding excess power back to the grid, but part of a coordinated local energy community[50][51][21]. Generally, these studies suggest a layered distributed-energy pathway for Pakistan. In cities, rooftop PV, batteries, and smart meters can support prosumers and reduce bills; in rural and remote areas, hybrid microgrids and nanogrids can provide reliable power where the main grid performs poorly; and across both settings, storage, local control, and energy trading can connect these smaller systems into a smarter and more flexible national energy architecture[52].

5. Policy, Implementation Barriers and Research Gaps

5.1 Policies, Targets, and Market Instruments in Pakistan

Pakistan has introduced renewable energy targets and policy measures to encourage clean energy development. These include rooftop solar approvals, net metering systems, and support mechanisms for independent power producers (IPPs). However, the literature indicates that a noticeable gap still exists between policy ambitions and the actual share of renewable energy in the national energy mix. This suggests that stronger integration strategies, clearer implementation

frameworks, and more effective regulatory mechanisms are still needed to achieve long-term renewable energy goals. National renewable targets have been set, but progress remains partial. Pakistan aims to raise the share of renewable power generation to 25% by 2025 and 30% by 2030. At the same time, one 2022 study notes that solar, wind, and biomass together still made up only 5.36% of installed capacity in the national grid, which shows that targets are ahead of actual deployment. NEPRA-backed rooftop solar is a key market instrument. The literature identifies the National Electric Power Regulatory Authority as an important enabler of grid-tied rooftop solar PV, with installations rising strongly in 2021. This makes rooftop solar one of the clearest policy-backed entry points for distributed renewable integration in Pakistan[53]. Net metering is helping create a distributed solar market. The same study reports that net-metered distributed generation had reached 398 MW by March 2022, showing that policy support is not limited to utility-scale projects and is also shaping consumer-side investment. Pakistan is also using multiple supply-side channels, not just rooftop PV. The policy mix discussed in the literature includes bagasse-based captive generation and the use of solar- and wind-based independent power plants, which broadens the renewable market beyond households and commercial rooftops. Policy attention covers both renewable integration and efficient energy use. One review highlights that the National Power Policy / related national power measures (NMP) focus on integrating renewable energy resources, while the Energy Efficiency and Conservation Act (EECA) is more focused on efficiency measures and standardization. This matters because Pakistan's transition depends not only on adding renewable generation, but also on lowering waste and improving how electricity is used. The literature also discusses a wider policy package around the energy crisis. Abbas et al. link renewable integration and efficiency to broader policy discussions around EWP, NMP, and EIP, arguing that these frameworks need to be understood together when judging Pakistan's energy transition response[54]. Scenario-based planning is itself presented as a policy tool. Rana

et al. use the EnergyPLAN model to test national electricity scenarios for Pakistan and argue that high renewable integration needs appropriate schemes and country-specific energy policy. In other words, the issue is not only whether Pakistan wants more renewables, but which policy design can integrate them without worsening system stress. A main policy message is that renewable integration is unavoidable, but it must be governed well. The studies do not treat renewable expansion as optional; they present it as necessary for easing Pakistan's energy crisis. But they also stress that policy targets alone are not enough unless they are matched by workable integration rules, planning models, and implementation mechanisms.

5.2 Implementation Barriers and Research Gaps

Pakistan's major challenge is no longer recognizing the importance of renewable energy and smart grids, but developing the financial resources, technical expertise, and grid infrastructure required for large-scale implementation. The literature also identifies an important research gap: although many proposed solutions appear technically promising, there is still limited work on practical deployment models, local technical capacity, and real-world renewable integration under Pakistan's actual grid conditions.

A consistent message in the literature is that implementation barriers in Pakistan are as much institutional and practical as they are technical. Even where solar, wind, microgrids, and smart-grid tools look attractive on paper, projects can stall because grid integration remains difficult, upfront costs are high, and utilities and developers need more specialized skills and technologies to plan, install, and operate these systems well. These constraints matter across both large renewable projects and distributed systems, because each depends on a grid and workforce that can handle new control methods, digital devices, and variable generation. (Bensadi, 2024). A second barrier is the gap between research prototypes and broad deployment. Pakistan-focused work shows strong academic interest in solar PV integration, microgrids, smart-grid technologies, rural electrification, and reliable urban PV performance,

which suggests that the knowledge base is growing. But it also implies an unfinished transition: many important topics are still being developed as research agendas rather than fully scaled operating practice, especially for low-cost rural architectures and high-performance urban renewable systems[55]. Taken together, these studies point to several clear research gaps for Pakistan. First, more work is needed on implementation-ready business and financing models that can reduce the burden of high initial investment for both utilities and consumers. Second, Pakistan needs more applied research on workforce training, standards, and local technical capacity so that smart-grid and renewable systems can be operated reliably after installation. Third, the country needs more field-based studies on how different renewable and smart-grid designs perform under Pakistan's actual network constraints, rather than only under ideal simulation settings. In short, the next phase for Pakistan is not only to prove that smart grids and renewable integration can work, but to show how they can be delivered affordably, operated reliably, and maintained at scale[55].

5.3 Challenges, Risks, and Implementation Barriers

Pakistan's smart-grid challenges are no longer limited to hardware and infrastructure alone. The more complex issues now involve securing an increasingly digitalized grid against cyber risks, preparing the energy system for climate-related shocks, and coordinating smart-grid expansion with regional interconnections and long-term system resilience planning. These challenges highlight the need for integrated technical, regulatory, and institutional strategies to support sustainable grid modernization. A key challenge is that smart grids make the power system more digital and more connected, which also makes it more exposed to cyber risk. Recent work on Pakistan explicitly frames smart-grid design around "rising cyber threats and increasing energy demand," showing that security has to be treated as a core design issue rather than an add-on after deployment. In practice, this means Pakistan will need stronger protection for meters, control systems, communications links, and utility data

platforms if it wants smart-grid functions to scale safely. Climate stress is another major barrier because smarter operation still depends on infrastructure that can withstand heat, storms, flooding, and changing load patterns. Recent Pakistan-focused studies stress the "critical role" of advanced grid technologies in building climate-resilient power infrastructure and call for climate-resilient grid planning, including lessons from southern Pakistan for utilities and policymakers. This adds an implementation risk that goes beyond normal grid modernization: if smart-grid investment is not paired with resilience planning, digital upgrades may sit on top of physical assets that remain vulnerable to weather and climate shocks. There is also a system-planning challenge linked to cross-border power exchange. Pakistan has potential HVAC interconnections with India and Afghanistan, and even wider regional links through India to countries such as Nepal. While this opens useful options for trade and balancing, it also raises the difficulty of synchronization, operating standards, protection coordination, and cross-border governance in any future smarter and more interconnected grid. Put simply, the more Pakistan connects internally and regionally, the more important interoperability, security, and coordinated planning become. Taken together, the literature suggests that Pakistan's smart-grid barrier is not only "how to install new technology," but how to build a secure, climate-resilient, and well-coordinated power system around it. That shifts the implementation task from simple equipment rollout to a broader program of cybersecurity, resilience planning, utility capability building, and regional coordination.

5.4 Expected Benefits and Future Directions

The main expected benefit of smart grids in Pakistan is not only improved electricity control, but also stronger economic efficiency at both the consumer and system levels. The literature suggests that future development should move beyond isolated microgrids and pilot projects toward interconnected, multi-microgrid smart systems supported by advanced net metering, intelligent energy management, and clearer measurement of economic and environmental

impacts, including cost reduction and emission savings. Based on previous literature, suggests that Pakistan can get the most value when smart-grid elements are combined rather than deployed one by one. In particular, future work is expected to test how several microgrids can be integrated into a centralized, grid-connected smart system for residential areas, so that technical and financial gains can be measured together rather than separately. This points to a practical future direction for Pakistan: move beyond isolated demonstrations and build coordinated local smart-grid clusters that can share power, smooth peaks, and use distributed resources more efficiently. A second expected benefit is better consumer economics through smarter settlement and pricing. Zaidi et al. argue that advanced net metering should be integrated into these smart residential systems to manage electricity economics in areas with multiple peak loads, which implies more accurate treatment of imports, exports, and local balancing. For Pakistan, this matters because future smart-grid value will likely depend not only on engineering performance, but also on whether households and prosumers see clear bill savings and fair compensation for distributed generation[21]. The same study also highlights two outcome measures that should shape future deployment: cost of energy and carbon emissions. In other words, the next phase for Pakistan is not simply to ask whether smart-grid technology works, but whether it lowers energy cost and reduces emissions when combined with advanced metering and coordinated local grids. If that evidence is built through residential and community-scale projects, it would give Pakistan a stronger basis for scaling smart grids in cities, new housing areas, and weak-grid regions while also supporting cleaner power growth.

6. Conclusion

This review has shown that smart grid development is becoming an important requirement for Pakistan's future electricity system. The country is facing rising demand, weak transmission and distribution performance, electricity theft, ageing infrastructure, and continuing reliability problems. At the same time,

Pakistan has strong solar, wind, hydropower, and distributed energy potential, especially in regions such as Sindh. These conditions make smart grid modernization necessary, not only for adding renewable energy, but also for improving the way electricity is monitored, controlled, delivered, and used.

The discussion also suggests that Pakistan is still in a gradual transition stage. Policies such as net metering, renewable energy targets, and energy efficiency measures have created a useful foundation, but implementation remains uneven. Smart meters, IoT-based monitoring, demand-side management, microgrids, storage systems, HVDC transmission, and better communication networks can all support renewable energy integration. However, these technologies will only be effective if they are supported by investment, technical skills, cybersecurity planning, public awareness, and stronger institutional coordination.

Overall, smart grids offer Pakistan a practical pathway towards a more reliable, flexible, and renewable-ready power system. For Sindh and other weak-grid regions, the benefits could include lower losses, improved fault detection, better integration of rooftop solar and microgrids, stronger resilience during climate-related disruptions, and more active consumer participation. The main challenge now is to move from policy intention and pilot-level research towards coordinated, affordable, and large-scale implementation.

7. Future Recommendations

7.1 Upgrade Transmission and Distribution Infrastructure

Pakistan should prioritize the replacement and reinforcement of ageing transmission lines, transformers, substations, and distribution feeders. This would reduce technical losses, improve voltage stability, and create a stronger base for renewable energy integration.

7.2 Expand Smart Metering and Automated Monitoring

Smart meters and automated metering infrastructure should be introduced more widely, particularly in high-loss areas. This can improve

billing accuracy, reduce electricity theft, detect abnormal consumption patterns, and support better load forecasting.

7.3 Strengthen Renewable Energy Integration Planning

Solar, wind, rooftop PV, and distributed generation projects should be planned together with grid capacity studies, forecasting tools, inverter standards, and voltage-management strategies. This would help avoid local network problems as renewable penetration increases.

7.4 Develop Microgrids and Storage for Weak-Grid Areas

Hybrid microgrids, battery storage, and local energy management systems should be encouraged in rural, remote, and unreliable-grid regions. These systems can improve resilience, reduce dependence on long transmission lines, and support cleaner local power supply.

7.5 Improve Cybersecurity and Climate Resilience

Cybersecurity protection should be built into smart grid systems from the beginning. At the same time, grid planning should consider floods, heatwaves, storms, and rising cooling demand so that digital upgrades are supported by physically resilient infrastructure.

7.6 Build Skills, Public Awareness, and Institutional Coordination

Training programmes should be developed for engineers, technicians, utility staff, and policymakers working with smart grid technologies. Public awareness campaigns are also needed so that consumers understand smart meters, energy conservation, net metering, and responsible electricity use.

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