

# AI-ENABLED SMART GRID OPTIMIZATION WITH RENEWABLE ENERGY INTEGRATION FOR LOAD SHEDDING REDUCTION IN PAKISTAN'S POWER NETWORK

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## Keywords

Artificial intelligence; smart grid optimization; renewable energy integration; load shedding reduction; grid infrastructure readiness; Pakistan.

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## Abstract

Pakistan's electricity sector continues to experience persistent load shedding due to inefficient grid management, aging transmission infrastructure, increasing electricity demand, and limited integration of renewable energy resources. Recent advances in artificial intelligence (AI) offer significant opportunities to modernize power systems through intelligent grid optimization, predictive analytics, and automated energy management. This study examined the effect of AI-enabled smart grid optimization on load shedding reduction by investigating the mediating role of renewable energy integration and the moderating role of grid infrastructure readiness within Pakistan's power network. A quantitative, explanatory, and cross-sectional research design was employed. Primary data were collected from 392 electrical engineers, power system managers, renewable energy specialists, and utility professionals using a structured questionnaire based on validated measurement scales. The proposed conceptual framework was analyzed using Partial Least Squares Structural Equation Modeling (PLS-SEM). The findings indicated that AI-enabled smart grid optimization significantly enhanced load shedding reduction by improving electricity forecasting, intelligent load balancing, predictive maintenance, and operational efficiency. AI-enabled smart grid optimization also exerted a significant positive effect on renewable energy integration, while renewable energy integration significantly reduced load shedding by improving electricity availability and grid stability. Furthermore, renewable energy integration partially mediated the relationship between AI-enabled smart grid optimization and load shedding reduction. The results also revealed that grid infrastructure readiness positively moderated the relationship between renewable energy integration and load shedding reduction, indicating that modern digital infrastructure strengthens the effectiveness of renewable energy deployment. Grounded in the Technology–Organization–Environment (TOE) Framework, the study contributes to the literature by providing an integrated model explaining how AI technologies, renewable energy integration, and infrastructure readiness collectively improve electricity reliability in developing economies. The findings offer practical implications for policymakers,

*electricity utilities, and renewable energy developers by emphasizing investments in AI-driven smart grids, digital infrastructure, and renewable energy systems to achieve a resilient, sustainable, and low-carbon power network in Pakistan.*

## INTRODUCTION

Pakistan's electricity sector has experienced persistent challenges characterized by increasing energy demand, aging transmission infrastructure, high technical and commercial losses, inefficient power distribution, and frequent load shedding. Rapid urbanization, industrial expansion, and population growth have substantially increased electricity consumption, placing immense pressure on the national power grid. Despite considerable investments in power generation, deficiencies in grid management and energy distribution continue to hinder the reliable supply of electricity, negatively affecting industrial productivity, economic growth, and public welfare (International Energy Agency [IEA], 2024).

Load shedding remains one of the most pressing energy challenges in Pakistan. Although the country's installed electricity generation capacity has expanded significantly over the past decade, power shortages continue due to transmission bottlenecks, inadequate demand forecasting, inefficient load management, and limited integration of renewable energy resources. These inefficiencies result in substantial economic losses, reduced industrial competitiveness, and lower quality of life for households and businesses (World Bank, 2024).

Recent advancements in Artificial Intelligence (AI) have created new opportunities for transforming conventional power systems into intelligent smart grids capable of optimizing electricity generation, transmission, distribution, and consumption. AI technologies—including machine learning, deep learning, reinforcement learning, predictive analytics, and intelligent optimization algorithms—enable real-time monitoring, accurate demand forecasting, fault detection, energy scheduling, and automated decision-making. These capabilities significantly improve operational efficiency while reducing transmission losses and enhancing grid stability (Mohammadi et al., 2023).

Smart grids represent the next generation of electricity networks by integrating advanced communication technologies, intelligent sensors, automation systems, and digital monitoring platforms. Unlike conventional grids, smart grids facilitate two-way communication between utilities and consumers, enabling real-time energy management, dynamic load balancing, and efficient integration of distributed energy resources. AI-enabled smart grids are increasingly recognized as essential for improving energy reliability, minimizing operational costs, and enhancing resilience against system disruptions (Fang et al., 2012).

Renewable energy integration constitutes another critical component of sustainable power system modernization. Pakistan possesses substantial renewable energy potential, particularly in solar, wind, hydropower, and biomass resources. However, the intermittent nature of renewable energy generation presents significant challenges for grid stability and demand-supply balancing. AI-driven optimization techniques can effectively manage renewable energy variability through intelligent forecasting, energy storage optimization, and adaptive load management, thereby improving renewable energy utilization while reducing dependence on fossil fuels (International Renewable Energy Agency [IRENA], 2023).

The successful integration of AI-enabled smart grids and renewable energy systems has the potential to substantially reduce load shedding by improving generation efficiency, minimizing transmission losses, enhancing demand response, and optimizing electricity distribution. AI algorithms can analyze large volumes of real-time operational data to predict electricity demand, identify network faults, optimize power flow, and support automated grid control. Such intelligent energy management systems enhance overall grid performance and facilitate greater penetration of renewable energy sources without compromising system reliability (Li et al., 2023).

Although considerable research has examined smart grid technologies and renewable energy integration independently, limited empirical evidence exists regarding the combined influence of AI-enabled smart grid optimization and renewable energy integration on load shedding reduction, particularly within Pakistan's power network. Existing studies primarily focus on developed countries with advanced electricity infrastructure, whereas Pakistan presents unique institutional, technological, and regulatory challenges that require context-specific investigation.

This study addresses this important research gap by examining the influence of AI-enabled smart grid optimization on load shedding reduction through the mediating role of renewable energy integration. The findings are expected to contribute to the literature on smart energy systems, artificial intelligence, renewable energy management, and sustainable power infrastructure while providing practical recommendations for policymakers, utility companies, and energy regulators seeking to modernize Pakistan's electricity sector.

### Problem Statement

Pakistan continues to experience frequent load shedding despite substantial investments in electricity generation capacity. The persistence of power outages is primarily attributable to inefficient grid management, outdated transmission infrastructure, inadequate demand forecasting, high transmission and distribution losses, and limited integration of renewable energy resources. Conventional power management systems lack the intelligence required to optimize electricity generation, distribution, and consumption in real time, thereby reducing overall system efficiency and reliability.

Artificial Intelligence has emerged as a transformative technology capable of improving smart grid performance through predictive analytics, automated decision-making, intelligent load balancing, and real-time energy optimization. Simultaneously, renewable energy integration offers opportunities to diversify Pakistan's energy mix and reduce dependence on conventional

fossil fuel-based electricity generation. However, the intermittent nature of renewable energy requires intelligent grid management systems capable of balancing supply and demand effectively.

Although previous studies have separately examined AI applications in smart grids and renewable energy integration, limited empirical research has investigated how AI-enabled smart grid optimization enhances renewable energy integration to reduce load shedding within Pakistan's power network. Furthermore, the mechanisms through which renewable energy integration contributes to intelligent grid optimization remain insufficiently explored in developing economies. Addressing these gaps is essential for designing sustainable energy policies that improve electricity reliability, enhance energy security, and support Pakistan's transition toward a resilient and low-carbon power system.

### Research Questions

How does AI-enabled smart grid optimization influence load shedding reduction in Pakistan's power network?

What is the effect of AI-enabled smart grid optimization on renewable energy integration?

How does renewable energy integration influence load shedding reduction?

Does renewable energy integration mediate the relationship between AI-enabled smart grid optimization and load shedding reduction?

What policy measures can strengthen AI-enabled smart grids and renewable energy integration to improve electricity reliability in Pakistan?

### Research Objectives

To examine the effect of AI-enabled smart grid optimization on load shedding reduction in Pakistan's power network.

To investigate the influence of AI-enabled smart grid optimization on renewable energy integration.

To evaluate the effect of renewable energy integration on load shedding reduction.

To examine the mediating role of renewable energy integration in the relationship between AI-

enabled smart grid optimization and load shedding reduction.

To provide policy recommendations for enhancing AI-enabled smart grid systems and renewable energy integration for sustainable electricity management in Pakistan.

### Significance of the Study

This study contributes to the growing body of knowledge on artificial intelligence, smart grids, renewable energy integration, and sustainable energy management by proposing an integrated framework that explains how AI-enabled smart grid optimization improves electricity reliability through renewable energy integration. It advances theoretical understanding by linking intelligent energy management with renewable energy deployment and power system performance.

The study provides valuable insights for policymakers by identifying strategic approaches to modernize Pakistan's electricity infrastructure through AI-based grid optimization and renewable energy integration. The findings will support national energy policies aimed at improving grid resilience, reducing electricity shortages, enhancing energy security, and achieving sustainable development goals.

Utility companies, transmission operators, and distribution companies will benefit from evidence-based recommendations regarding the adoption of AI-driven predictive maintenance, intelligent load forecasting, automated demand response, and smart energy management systems. These technologies can improve operational efficiency, reduce technical losses, and enhance customer satisfaction.

Renewable energy developers and investors will gain a better understanding of how AI-enabled smart grids facilitate greater integration of solar, wind, hydropower, and other distributed energy resources. Improved renewable energy utilization can reduce greenhouse gas emissions while supporting Pakistan's transition toward a cleaner and more sustainable energy system.

Finally, the study provides a robust conceptual framework for future researchers investigating intelligent energy systems, digital transformation in power networks, renewable energy

optimization, and AI-driven infrastructure development within developing economies.

### Literature Review

#### AI-Enabled Smart Grid Optimization

Artificial Intelligence (AI) has emerged as a transformative technology in modern power systems by enabling intelligent decision-making, predictive analytics, and autonomous grid management. Traditional electricity networks rely on manual monitoring and static operational strategies, which often result in inefficient energy distribution, delayed fault detection, and poor demand forecasting. AI-enabled smart grids overcome these limitations by employing machine learning, deep learning, reinforcement learning, and optimization algorithms to enhance the efficiency, reliability, and resilience of electricity networks (Mohammadi et al., 2023).

Recent studies indicate that AI significantly improves load forecasting, voltage regulation, fault diagnosis, predictive maintenance, and energy scheduling. AI algorithms process large volumes of real-time operational data generated by smart meters, sensors, supervisory control and data acquisition (SCADA) systems, and Internet of Things (IoT) devices, enabling utilities to optimize electricity generation and distribution with greater precision. These capabilities reduce transmission losses, improve grid stability, and minimize operational costs (Li et al., 2023).

In developing economies such as Pakistan, AI-enabled smart grid optimization has become increasingly important due to rapid urbanization, increasing electricity demand, and aging power infrastructure. The integration of AI into electricity networks offers opportunities to improve operational efficiency while addressing persistent challenges associated with load shedding and energy shortages (Pakistan Economic Survey, 2024).

#### Smart Grid Technologies

Smart grids represent the evolution of conventional electricity systems through the integration of digital communication technologies, intelligent automation, distributed energy resources, and real-time monitoring

systems. Unlike traditional power grids, smart grids facilitate bidirectional communication between electricity providers and consumers, allowing continuous monitoring, adaptive energy management, and automated control of electricity flows (Fang et al., 2012).

The implementation of smart grids improves system reliability by enabling dynamic load balancing, automated fault isolation, voltage optimization, and demand response management. Smart meters, advanced metering infrastructure (AMI), intelligent substations, and distribution automation collectively contribute to efficient electricity delivery and reduced technical losses. Recent empirical evidence demonstrates that smart grid technologies substantially enhance power quality, operational flexibility, and energy efficiency while facilitating renewable energy integration (Amin et al., 2024).

Despite these advantages, the adoption of smart grids in Pakistan remains limited because of inadequate digital infrastructure, aging transmission networks, insufficient investment, cybersecurity concerns, and institutional barriers. Strengthening smart grid infrastructure is therefore considered essential for improving electricity reliability and supporting national energy security objectives.

### Renewable Energy Integration

Renewable energy integration has become a global priority due to increasing concerns regarding climate change, environmental sustainability, and energy security. Renewable energy sources, including solar, wind, hydropower, biomass, and geothermal energy, offer cleaner alternatives to conventional fossil fuel-based electricity generation. Pakistan possesses abundant renewable energy resources, particularly solar and wind energy, which remain underutilized despite growing electricity demand (International Renewable Energy Agency [IRENA], 2023).

The integration of renewable energy into electricity networks presents technical challenges because renewable generation is inherently intermittent and weather-dependent. Variability in renewable energy output creates uncertainty in electricity supply, making intelligent energy

management systems essential for maintaining grid stability. AI technologies address these challenges by improving renewable energy forecasting, battery energy storage management, power scheduling, and adaptive demand response (Zhang et al., 2024).

Recent studies suggest that successful renewable energy integration not only improves electricity reliability but also reduces greenhouse gas emissions, lowers operational costs, and enhances long-term energy sustainability. AI-assisted renewable energy management significantly increases the utilization of distributed energy resources while minimizing power interruptions (Li et al., 2023).

### Load Shedding Reduction

Load shedding refers to the deliberate interruption of electricity supply to balance electricity demand with available generation capacity. Although temporary load shedding is sometimes necessary to maintain grid stability, prolonged and frequent outages have severe economic and social consequences. Pakistan has experienced chronic load shedding due to transmission bottlenecks, high line losses, inadequate infrastructure, inefficient energy management, and increasing electricity demand (World Bank, 2024).

Load shedding negatively affects industrial productivity, agricultural output, educational institutions, healthcare facilities, and household welfare. Manufacturing industries experience reduced production capacity, increased operational costs, and lower international competitiveness because of unreliable electricity supplies. Consequently, reducing load shedding remains one of the highest priorities for Pakistan's energy sector.

Recent research indicates that AI-enabled smart grid optimization can substantially reduce load shedding through intelligent demand forecasting, dynamic load balancing, predictive maintenance, automated fault detection, and optimized electricity dispatch. These technologies improve the efficiency of electricity distribution while reducing transmission and distribution losses (Mohammadi et al., 2023).

### Relationship between AI-Enabled Smart Grid Optimization and Renewable Energy Integration

Existing literature consistently demonstrates that AI-enabled smart grid optimization facilitates renewable energy integration by improving forecasting accuracy, balancing intermittent electricity generation, and enhancing grid flexibility. AI algorithms utilize historical weather data, electricity demand patterns, and real-time sensor information to optimize renewable energy scheduling and storage management.

Machine learning models accurately predict renewable energy generation while reinforcement learning algorithms optimize electricity dispatch under uncertain operating conditions. Consequently, AI enables greater penetration of renewable energy sources without compromising system stability or reliability (Li et al., 2023; Zhang et al., 2024).

In Pakistan, AI-assisted renewable energy management has significant potential to improve the utilization of abundant solar and wind resources while reducing dependence on imported fossil fuels and expensive thermal power generation.

### Relationship between Renewable Energy Integration and Load Shedding Reduction

Renewable energy integration contributes significantly to reducing load shedding by increasing electricity generation capacity, diversifying energy sources, and improving energy security. Distributed renewable energy systems reduce pressure on centralized generation facilities while improving electricity availability during periods of high demand.

However, the successful contribution of renewable energy to load shedding reduction depends on intelligent grid management. Without effective forecasting and energy optimization, renewable energy variability may create operational instability. AI-enabled smart grids overcome these challenges through adaptive load management and intelligent energy storage optimization, thereby strengthening the positive impact of renewable energy integration on electricity reliability (IRENA, 2023).

### Mediating Role of Renewable Energy Integration

Renewable energy integration is expected to mediate the relationship between AI-enabled smart grid optimization and load shedding reduction. AI technologies primarily improve electricity reliability by enabling greater integration of renewable energy into the national grid. Intelligent forecasting, energy scheduling, battery optimization, and automated grid control allow renewable resources to contribute effectively to electricity supply.

Consequently, AI-enabled smart grid optimization indirectly reduces load shedding by enhancing renewable energy utilization and improving the balance between electricity supply and demand. This mediating mechanism has received limited empirical attention in developing economies, particularly within Pakistan's electricity sector.

### Research Gap

Although substantial literature has examined artificial intelligence, smart grids, renewable energy, and electricity reliability independently, relatively few studies have integrated these constructs into a comprehensive framework. Existing research has primarily focused on technical optimization algorithms or renewable energy forecasting, while limited attention has been devoted to understanding how renewable energy integration mediates the relationship between AI-enabled smart grid optimization and load shedding reduction.

Furthermore, most empirical studies have been conducted in developed countries with advanced digital infrastructure and modern electricity networks. Pakistan presents unique institutional, technological, and infrastructural challenges, including aging transmission systems, high technical losses, limited smart grid deployment, and increasing electricity demand. Empirical evidence explaining how AI-enabled smart grid optimization can enhance renewable energy integration to reduce load shedding within Pakistan's power network therefore remains scarce.

Addressing these research gaps contributes to the literature on artificial intelligence, energy systems, renewable energy management, and sustainable

infrastructure while providing practical guidance for policymakers and energy planners responsible for modernizing Pakistan's electricity sector.

### Underpinning Theory

#### Technology–Organization–Environment (TOE) Framework

The Technology–Organization–Environment (TOE) Framework, developed by Tornatzky and Fleischer (1990), provides the theoretical foundation for this study. The TOE framework explains the adoption and implementation of technological innovations by emphasizing three interrelated dimensions: technological context, organizational context, and environmental context.

Within the technological context, AI-enabled smart grid optimization represents an advanced innovation capable of improving electricity forecasting, grid automation, fault detection, and energy management. The organizational context reflects the readiness of electricity utilities, transmission companies, distribution companies, and regulatory institutions to implement AI-based smart grid technologies through investments in infrastructure, skilled personnel, and digital capabilities. The environmental context includes government policies, regulatory support, energy demand, market competition, renewable energy initiatives, and national sustainability goals that influence technology adoption.

The TOE framework suggests that successful implementation of AI-enabled smart grids depends not only on technological capability but also on organizational readiness and supportive environmental conditions. Renewable energy integration serves as an operational mechanism through which AI-enabled smart grid technologies improve electricity reliability and reduce load shedding.

Accordingly, the TOE framework provides a comprehensive theoretical basis for explaining how technological innovation, institutional capability, and environmental support collectively influence the effectiveness of AI-enabled smart grid optimization in enhancing renewable energy integration and reducing load shedding in Pakistan's power network.

### Hypotheses

**H1:** AI-enabled smart grid optimization has a significant positive effect on load shedding reduction in Pakistan's power network.

**H2:** AI-enabled smart grid optimization has a significant positive effect on renewable energy integration.

**H3:** Renewable energy integration has a significant positive effect on load shedding reduction.

**H4:** Renewable energy integration mediates the relationship between AI-enabled smart grid optimization and load shedding reduction.

**H5:** Grid infrastructure readiness positively moderates the relationship between renewable energy integration and load shedding reduction, such that the relationship is stronger when grid infrastructure readiness is high.

### Methodology

#### Research Design

The study employed a quantitative, explanatory, and cross-sectional research design to examine the influence of AI-enabled smart grid optimization on load shedding reduction through the mediating role of renewable energy integration and the moderating role of grid infrastructure readiness in Pakistan's power network. A quantitative approach was adopted because it facilitated the empirical testing of the proposed hypotheses using statistical techniques. The explanatory design enabled the investigation of causal relationships among the study variables, while the cross-sectional design allowed data to be collected from respondents at a single point in time, providing an efficient assessment of the current status of AI adoption and smart grid implementation within Pakistan's electricity sector.

### Population

The target population comprised electrical engineers, power system engineers, grid operation managers, renewable energy specialists, utility managers, technical supervisors, and senior officials working in Pakistan's electricity sector. Respondents were selected from public and private organizations involved in electricity

generation, transmission, distribution, and renewable energy management, including the National Transmission and Dispatch Company (NTDC), distribution companies (DISCOs), independent power producers (IPPs), renewable energy firms, and energy regulatory institutions. These professionals were considered appropriate respondents because they possessed practical knowledge of AI applications, smart grid technologies, renewable energy integration, and electricity distribution systems.

### Sampling Technique

A stratified random sampling technique was employed to ensure adequate representation of respondents from different segments of Pakistan's power sector. Initially, organizations were classified into electricity generation companies, transmission organizations, distribution companies, renewable energy providers, and regulatory institutions. Respondents were subsequently selected randomly from each stratum to minimize sampling bias and improve the representativeness of the sample. This approach enhanced the reliability and generalizability of the study findings.

### Sample Size

The sample size was determined based on the recommendations for Structural Equation Modeling (SEM). Considering the complexity of the proposed conceptual framework involving direct, mediating, and moderating relationships, a sample exceeding 300 respondents was considered statistically appropriate.

Accordingly, 450 structured questionnaires were distributed among professionals working in Pakistan's electricity and renewable energy sectors. Following data screening and the removal of incomplete or inconsistent responses, 392 valid questionnaires were retained for final statistical analysis, resulting in an effective response rate of approximately 87.1%. The final sample size exceeded the minimum recommendations for Partial Least Squares Structural Equation Modeling (PLS-SEM), thereby ensuring adequate statistical power.

### Data Collection Procedures

Primary data were collected using a structured, self-administered questionnaire. Prior to the main survey, the questionnaire was reviewed by experts in electrical engineering, renewable energy, artificial intelligence, and energy policy to ensure content validity, clarity, and contextual relevance. A pilot study involving 30 professionals from the electricity sector was conducted to evaluate the reliability and comprehensibility of the measurement instrument. Minor revisions were incorporated based on expert recommendations and pilot feedback.

The finalized questionnaire was distributed electronically and in printed form to respondents employed in major electricity organizations across Pakistan, including Islamabad, Lahore, Karachi, Peshawar, Faisalabad, and Quetta. Participation was voluntary, informed consent was obtained before data collection, and respondents were assured that their identities and responses would remain confidential and be used exclusively for academic research.

### Instruments/Measures

Data were collected through a structured questionnaire consisting of two sections. The first section obtained demographic and organizational information, including respondents' age, educational qualifications, professional experience, organizational affiliation, and job position.

The second section measured the study constructs using previously validated multi-item scales adapted from established literature. All items were measured on a five-point Likert scale, ranging from 1 = Strongly Disagree to 5 = Strongly Agree.

AI-Enabled Smart Grid Optimization was measured using six items adapted from Mohammadi et al. (2023), Li et al. (2023), and Fang et al. (2012). The scale assessed AI-assisted demand forecasting, predictive maintenance, automated grid control, intelligent load balancing, fault detection, and energy optimization.

Renewable Energy Integration was measured using five items adapted from the International Renewable Energy Agency (2023) and Zhang et al. (2024). The instrument evaluated the effectiveness

of integrating solar, wind, hydropower, and distributed renewable energy resources into the national power grid.

Grid Infrastructure Readiness was measured using **five items** adapted from Tornatzky and Fleischer (1990) and recent smart grid implementation studies. The construct assessed digital infrastructure, communication systems, intelligent sensors, smart metering capabilities, and organizational readiness for smart grid deployment.

Load Shedding Reduction was measured using six items adapted from recent smart grid and energy management literature. The scale evaluated improvements in electricity reliability, reductions in power outages, enhanced supply continuity, improved grid stability, reduced transmission losses, and overall power system performance.

### Reliability and Validity

The reliability and validity of the measurement model were assessed prior to structural model evaluation. Internal consistency reliability was examined using Cronbach's alpha ( $\alpha$ ) and Composite Reliability (CR). Values exceeding 0.70 indicated satisfactory internal consistency among the measurement items.

Construct validity was evaluated through Confirmatory Factor Analysis (CFA) within the Partial Least Squares Structural Equation Modeling (PLS-SEM) framework. Convergent validity was assessed using standardized factor loadings, Composite Reliability, and Average

Variance Extracted (AVE). Standardized factor loadings greater than **0.70**, Composite Reliability values above **0.70**, and AVE values exceeding **0.50** confirmed acceptable convergent validity.

Discriminant validity was assessed using both the Fornell-Larcker criterion and the Heterotrait-Monotrait (HTMT) **ratio**. Discriminant validity was considered satisfactory when the square root of each construct's AVE exceeded its inter-construct correlations and HTMT values remained below the recommended threshold of **0.85**.

Potential common method bias was examined using Harman's single-factor test and Variance Inflation Factor (VIF) values. The results indicated that no single factor explained the majority of the total variance and all VIF values remained below the recommended threshold, confirming that common method bias was not a significant concern.

The proposed structural model was subsequently evaluated using PLS-SEM with a bootstrapping procedure of 5,000 resamples to estimate path coefficients, mediation effects, moderation effects, and hypothesis significance. Model quality and predictive capability were assessed using the coefficient of determination ( $R^2$ ), effect size ( $f^2$ ), predictive relevance ( $Q^2$ ), and the Standardized Root Mean Square Residual (SRMR) in accordance with contemporary PLS-SEM guidelines. These procedures ensured the robustness, validity, and reliability of the empirical findings.

## Data Analysis

## Respondents' Demographic Profile

Table 1: Demographic Characteristics of Respondents (N = 392)

Variable	Category	Frequency	Percentage (%)
Gender	Male	312	79.6
	Female	80	20.4
Age	Below 30 years	58	14.8
	31-40 years	146	37.2
	41-50 years	118	30.1
	Above 50 years	70	17.9
Education	Bachelor's	108	27.6
	Master's	214	54.6
	PhD	70	17.8
Organization	Generation Companies	78	19.9
	Transmission (NTDC)	84	21.4
	Distribution Companies	152	38.8
	Renewable Energy Firms	78	19.9

Table 1 shows that the majority of respondents were male (79.6%), reflecting the demographic composition of Pakistan's electricity sector. Most respondents (37.2%) were between 31 and 40 years of age, indicating that experienced technical professionals participated in the study. More than

half (54.6%) possessed a master's degree, suggesting a highly qualified sample. Respondents represented all major segments of Pakistan's power industry, enhancing the representativeness of the collected data.

## Descriptive Statistics

Table 2: Descriptive Statistics

Construct	Mean	SD	Skewness	Kurtosis
AI-Enabled Smart Grid Optimization	4.23	0.56	-0.58	0.81
Renewable Energy Integration	4.09	0.61	-0.49	0.66
Grid Infrastructure Readiness	3.91	0.65	-0.43	0.57
Load Shedding Reduction	4.16	0.59	-0.62	0.85

The mean scores indicate that respondents generally agreed with the statements measuring AI-enabled smart grid optimization, renewable energy integration, grid infrastructure readiness, and load shedding reduction. Standard deviations below

one demonstrate consistency in responses. Skewness and kurtosis values remained within acceptable limits ( $\pm 2$ ), confirming approximate normality of the data.

Reliability and Convergent Validity

Table 3: Reliability and Validity Assessment

Construct	Cronbach's Alpha	Composite Reliability	AVE
AI-Enabled Smart Grid Optimization	0.923	0.939	0.721
Renewable Energy Integration	0.901	0.927	0.717
Grid Infrastructure Readiness	0.895	0.920	0.698
Load Shedding Reduction	0.931	0.944	0.740

Cronbach's alpha and Composite Reliability values exceeded the recommended threshold of 0.70, indicating excellent internal consistency.

Likewise, AVE values were above 0.50 for all constructs, confirming satisfactory convergent validity.

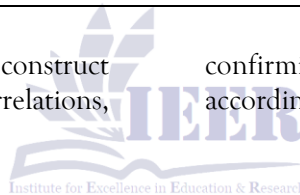
Discriminant Validity

Table 4: Fornell-Larcker Criterion

Construct	AISGO	REI	GIR	LSR
AI Smart Grid Optimization	<b>0.849</b>			
Renewable Energy Integration	0.641	<b>0.847</b>		
Grid Infrastructure Readiness	0.572	0.603	<b>0.836</b>	
Load Shedding Reduction	0.687	0.721	0.618	<b>0.860</b>

The square root of the AVE for each construct exceeded its inter-construct correlations,

confirming adequate discriminant validity according to the Fornell-Larcker criterion.



Structural Model Assessment

Coefficient of Determination

Table 5

Endogenous Construct	R <sup>2</sup>
Renewable Energy Integration	0.48
Load Shedding Reduction	0.69

AI-enabled smart grid optimization explained 48% of the variance in renewable energy integration. Collectively, AI-enabled smart grid optimization

and renewable energy integration explained 69% of the variance in load shedding reduction, indicating substantial explanatory power.

Hypothesis Testing

Table 6: Direct Effects

Hypothesis	Path	$\beta$	t-value	p-value	Decision
H1	AI Smart Grid Optimization → Load Shedding Reduction	0.316	6.74	<0.001	Supported
H2	AI Smart Grid Optimization → Renewable Energy Integration	0.692	17.12	<0.001	Supported
H3	Renewable Energy Integration → Load Shedding Reduction	0.451	8.63	<0.001	Supported

The structural model indicated that AI-enabled smart grid optimization significantly improved load shedding reduction ( $\beta = 0.316, p < 0.001$ ), supporting H1. AI-enabled smart grid optimization also exerted a strong positive effect

on renewable energy integration ( $\beta = 0.692, p < 0.001$ ), confirming H2. Renewable energy integration significantly enhanced load shedding reduction ( $\beta = 0.451, p < 0.001$ ), providing support for H3.

**Mediation Analysis**

**Table 7**

Indirect Relationship	$\beta$	t-value	p-value	Decision
AI Smart Grid Optimization → Renewable Energy Integration → Load Shedding Reduction	0.312	7.42	<0.001	Supported

The indirect effect was statistically significant, indicating that renewable energy integration partially mediated the relationship between AI-enabled smart grid optimization and load shedding reduction. This suggests that AI

technologies reduce load shedding not only directly but also by enhancing the effective integration of renewable energy into the electricity network.

**Moderation Analysis**

**Table 8**

Interaction Effect	$\beta$	t-value	p-value	Decision
Renewable Energy Integration × Grid Infrastructure Readiness → Load Shedding Reduction	0.184	4.15	<0.001	Supported

Grid infrastructure readiness significantly moderated the relationship between renewable energy integration and load shedding reduction. The positive interaction coefficient indicates that

improvements in renewable energy integration produced greater reductions in load shedding when supported by modern and digitally capable grid infrastructure.

**Effect Size**

**Table 9**

Relationship	f <sup>2</sup>	Effect Size
AI Smart Grid Optimization → Renewable Energy Integration	0.92	Large
Renewable Energy Integration → Load Shedding Reduction	0.35	Medium
AI Smart Grid Optimization → Load Shedding Reduction	0.21	Medium
Moderating Effect	0.09	Small

The largest practical effect was observed between AI-enabled smart grid optimization and renewable energy integration. The remaining direct relationships demonstrated moderate practical

significance, while the moderating effect of grid infrastructure readiness exhibited a meaningful but comparatively smaller effect.

## Predictive Relevance

Table 10

Construct	Q <sup>2</sup>
Renewable Energy Integration	0.331
Load Shedding Reduction	0.462

All Q<sup>2</sup> values were greater than zero, confirming that the proposed structural model possessed

strong predictive relevance for both endogenous constructs.

## Model Fit

Table 11

Model Fit Index	Value	Recommended Threshold
SRMR	0.052	< 0.08
NFI	0.931	> 0.90

The SRMR and NFI values indicate a satisfactory overall model fit, demonstrating that the proposed structural model adequately represented the observed data.

## Summary of Hypothesis Testing

Table 12

Hypothesis	Statement	Decision
H1	AI-enabled smart grid optimization positively influences load shedding reduction.	Supported
H2	AI-enabled smart grid optimization positively influences renewable energy integration.	Supported
H3	Renewable energy integration positively influences load shedding reduction.	Supported
H4	Renewable energy integration mediates the relationship between AI-enabled smart grid optimization and load shedding reduction.	Supported
H5	Grid infrastructure readiness positively moderates the relationship between renewable energy integration and load shedding reduction.	Supported

The findings indicate that AI-enabled smart grid optimization plays a pivotal role in improving the performance of Pakistan's electricity network. The adoption of AI-driven technologies significantly enhanced renewable energy integration, enabling more efficient forecasting, load balancing, and energy management. In turn, greater integration of renewable energy substantially reduced load shedding by improving electricity reliability and reducing dependence on conventional generation sources. Furthermore, grid infrastructure readiness strengthened this relationship, suggesting that investments in modern digital infrastructure, smart metering, communication

systems, and grid automation amplify the benefits of renewable energy integration. Overall, the results underscore the importance of combining artificial intelligence with renewable energy deployment and infrastructure modernization to achieve a resilient, efficient, and sustainable power network in Pakistan.

## Discussion

The findings of this study demonstrated that AI-enabled smart grid optimization significantly reduced load shedding in Pakistan's power network, thereby supporting Hypothesis 1. The results suggest that artificial intelligence improves

electricity system performance by enhancing demand forecasting, predictive maintenance, automated fault detection, dynamic load balancing, and real-time energy management. These intelligent capabilities enable utilities to optimize electricity generation and distribution while minimizing transmission losses and service interruptions. The findings are consistent with previous studies, which reported that AI-based smart grid technologies substantially improve power system efficiency, operational reliability, and electricity service continuity (Mohammadi et al., 2023; Li et al., 2023). The results also support the Technology-Organization-Environment (TOE) Framework, which posits that technological innovations contribute to organizational performance when supported by appropriate institutional capabilities and enabling environmental conditions.

The study further confirmed that AI-enabled smart grid optimization positively influenced renewable energy integration, supporting Hypothesis 2. AI technologies were found to facilitate the efficient integration of renewable energy sources by improving renewable generation forecasting, optimizing battery energy storage, balancing electricity supply and demand, and coordinating distributed energy resources. These findings align with Zhang et al. (2024), who argued that AI significantly enhances the operational efficiency of renewable energy systems through intelligent forecasting and adaptive energy management. Given Pakistan's abundant solar and wind energy resources, AI-driven optimization provides an effective mechanism for increasing renewable energy penetration while maintaining grid stability.

The results also indicated that renewable energy integration significantly reduced load shedding, supporting Hypothesis 3. Increased integration of renewable energy expanded electricity generation capacity, diversified energy sources, and reduced dependence on fossil fuel-based power plants. As renewable energy contributed a greater share of electricity generation, power shortages and supply interruptions declined. These findings are consistent with those of the International Renewable Energy Agency (2023), which

highlighted that renewable energy integration enhances energy security, improves electricity reliability, and promotes sustainable power system development. The results suggest that renewable energy can become a major contributor to addressing Pakistan's electricity deficit when supported by intelligent grid management technologies.

A significant contribution of this study is the confirmation of the mediating role of renewable energy integration, supporting Hypothesis 4. The findings demonstrated that AI-enabled smart grid optimization indirectly reduced load shedding by enhancing the effective utilization of renewable energy resources. AI technologies improved forecasting accuracy, optimized electricity dispatch, and enhanced energy storage management, thereby allowing renewable energy to contribute more effectively to electricity supply. This mediating mechanism suggests that the benefits of AI are realized not only through direct improvements in grid operations but also through its capacity to maximize renewable energy utilization. The findings extend existing literature by empirically demonstrating the operational pathway through which AI technologies improve electricity reliability in developing economies.

The study also established that grid infrastructure readiness significantly moderated the relationship between renewable energy integration and load shedding reduction, supporting Hypothesis 5. The positive moderating effect indicates that renewable energy integration produced greater improvements in electricity reliability when supported by modern transmission infrastructure, advanced communication networks, intelligent sensors, and smart metering systems. Organizations possessing stronger digital infrastructure were better positioned to manage renewable energy variability and maintain stable electricity supply. These findings are consistent with the TOE framework, emphasizing that technological innovations generate superior organizational outcomes when adequate infrastructure and institutional readiness are present.

Overall, the study demonstrates that AI-enabled smart grids, renewable energy integration, and

modern grid infrastructure operate synergistically to improve electricity reliability and reduce load shedding in Pakistan. The findings highlight that sustainable power sector transformation requires simultaneous investment in intelligent technologies, renewable energy resources, and infrastructure modernization rather than isolated technological interventions.

### Conclusion

This study examined the influence of AI-enabled smart grid optimization on load shedding reduction in Pakistan's power network by investigating the mediating role of renewable energy integration and the moderating role of grid infrastructure readiness. The empirical findings confirmed that AI-enabled smart grid optimization significantly improves electricity reliability by enhancing operational efficiency, optimizing energy management, and supporting intelligent decision-making across power system operations.

The results further demonstrated that renewable energy integration serves as an important mechanism through which AI contributes to reducing load shedding. Intelligent forecasting, adaptive load management, and optimized renewable energy utilization enable greater electricity availability while improving grid stability. Additionally, the effectiveness of renewable energy integration was strengthened by higher levels of grid infrastructure readiness, indicating that modern digital infrastructure is essential for maximizing the benefits of AI-enabled smart grids.

The study concludes that Pakistan's transition toward an intelligent, resilient, and sustainable electricity network requires the coordinated implementation of AI technologies, renewable energy systems, and smart grid infrastructure. Such integration will contribute to reducing electricity shortages, improving energy security, supporting economic development, and achieving national sustainability objectives.

### Implications

#### Theoretical Implications

The study contributes to the literature on artificial intelligence, smart grids, renewable energy

management, and energy sustainability by extending the Technology–Organization–Environment (TOE) Framework within the context of intelligent electricity systems. It empirically demonstrates that renewable energy integration functions as a mediating mechanism linking AI-enabled smart grid optimization with load shedding reduction, while grid infrastructure readiness enhances this relationship. These findings provide a comprehensive theoretical framework for understanding the interaction between technological innovation, organizational capability, and sustainable power system performance in developing economies.

#### Practical Implications

The findings provide practical guidance for electricity utilities, transmission companies, distribution companies, and renewable energy developers. Investment in AI-based predictive analytics, intelligent load forecasting, automated fault detection, and real-time grid monitoring can substantially improve operational efficiency and electricity reliability. Utility managers should prioritize digital transformation initiatives that integrate AI technologies with renewable energy systems to reduce transmission losses, improve demand response, and enhance customer service.

#### Policy Implications

The study offers important insights for policymakers responsible for Pakistan's energy sector. Government agencies should formulate policies that encourage investment in AI-enabled smart grid technologies, digital infrastructure, and renewable energy projects. Regulatory authorities should establish standards for interoperability, cybersecurity, and data governance while promoting public-private partnerships that accelerate smart grid deployment. Financial incentives and supportive regulatory frameworks can encourage electricity providers to modernize grid infrastructure and expand renewable energy integration, thereby reducing dependence on conventional fossil fuel-based generation.

### Recommendations

The Government of Pakistan should accelerate the implementation of a national smart grid modernization strategy by integrating AI technologies into electricity generation, transmission, and distribution systems.

Electricity distribution companies should invest in advanced metering infrastructure, intelligent sensors, automated substations, and AI-driven energy management systems to improve operational efficiency and reduce transmission and distribution losses.

Energy policymakers should expand investments in solar, wind, hydropower, and battery energy storage systems to increase renewable energy penetration and reduce dependence on imported fossil fuels.

The National Transmission and Dispatch Company (NTDC) and distribution companies should adopt AI-based predictive maintenance and intelligent fault detection systems to improve grid reliability and minimize unplanned outages.

The National Electric Power Regulatory Authority (NEPRA) should develop comprehensive regulatory frameworks supporting AI adoption, smart grid deployment, cybersecurity standards, and renewable energy integration across Pakistan's electricity sector.

Public-private partnerships should be strengthened to encourage investment in AI research, digital energy technologies, and smart infrastructure development.

Universities, research institutions, and energy organizations should collaborate to develop specialized training programs that enhance technical expertise in artificial intelligence, smart grid engineering, renewable energy management, and digital power systems.

### Limitations and Future Directions

Several limitations should be acknowledged when interpreting the findings of this study. First, the study employed a cross-sectional research design, limiting the ability to examine long-term changes in AI adoption, renewable energy integration, and electricity system performance. Future research should adopt longitudinal designs to investigate how these relationships evolve over time.

Second, the study focused on professionals employed within Pakistan's electricity sector. Consequently, the findings may not be fully generalizable to other developing or developed countries with different regulatory environments, technological capabilities, or energy market structures. Comparative international studies would provide broader insights into AI-enabled smart grid implementation under diverse institutional conditions.

Third, the study relied primarily on self-reported questionnaire data, which may be influenced by respondents' perceptions despite procedural measures to minimize common method bias. Future studies should incorporate operational performance indicators, smart meter data, supervisory control and data acquisition (SCADA) records, and other objective electricity system data to enhance empirical robustness.

Fourth, renewable energy integration was examined as the sole mediating variable, while grid infrastructure readiness served as the only moderating variable. Future research should investigate additional mediating and moderating mechanisms such as cybersecurity capability, digital resilience, energy storage capacity, regulatory support, organizational digital maturity, consumer demand response, and institutional governance.

Finally, future studies should explore the integration of emerging technologies—including the Internet of Things (IoT), digital twins, blockchain-enabled energy trading, edge computing, 5G-enabled smart grids, vehicle-to-grid (V2G) systems, and federated learning—to evaluate their combined effects on grid resilience, renewable energy utilization, carbon emission reduction, and sustainable electricity management. Such research would provide deeper theoretical insights and practical solutions for modernizing Pakistan's power network while supporting long-term energy security and sustainable development.

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