

RENEWABLE ENERGY INTEGRATION IN SMART ELECTRICAL NETWORKS: ADVANCED POWER SYSTEM STRATEGIES FOR SUSTAINABLE ENERGY TRANSITION

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DOI:

Keywords:

Artificial Intelligence-Based Optimization, Demand-Side Management, Energy Storage Systems, Renewable Energy Integration, Smart Electrical Networks, Sustainable Energy Transition

Article History

Received: 13 May, 2026

Accepted: 17 June, 2026

Published: 20 June, 2026

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Abstract

The integration of renewable energy resources into smart electrical networks emerged as a critical requirement for achieving sustainable energy transition and reducing dependence on fossil-fuel-based electricity generation. This study examined the influence of advanced power system strategies on renewable energy integration and sustainable energy transition within modern smart electrical networks. The research focused on Smart Grid Technologies, Energy Storage Systems, Demand-Side Management, and Artificial Intelligence-Based Optimization as key determinants of sustainable energy performance. A quantitative research design was employed, and data were collected from a sample of 320 professionals working in electricity utilities, renewable energy organizations, power system engineering firms, and energy regulatory agencies. Statistical analyses included descriptive statistics, Pearson correlation analysis, and multiple regression analysis. The findings indicated that Artificial Intelligence-Based Optimization exerted the strongest influence on Sustainable Energy Transition ($\beta = 0.385$, $p < 0.001$), followed by Smart Grid Technologies ($\beta = 0.341$, $p < 0.001$), Energy Storage Systems ($\beta = 0.298$, $p < 0.001$), and Demand-Side Management ($\beta = 0.267$, $p < 0.001$). Correlation analysis revealed significant positive relationships among all study variables, with Artificial Intelligence-Based Optimization demonstrating the strongest correlation with Sustainable Energy Transition ($r = 0.781$, $p < 0.01$). The regression model explained 69.4% of the variance in Sustainable Energy Transition ($R^2 = 0.694$). The study concluded that advanced power system strategies significantly enhanced renewable energy integration, improved grid efficiency, strengthened system reliability, and accelerated sustainable energy transition. The findings provided valuable implications for policymakers, utility providers, and energy planners seeking to develop resilient and environmentally sustainable electrical networks.

Introduction

Energy resources experienced a radical transformation in the wake of governments, industries and communities began to shift towards the energy technologies that will help them meet goals aimed at reducing climate change, boosting energy security and easing the pressure on electricity demand. Sustainable development would require the greater use of renewable energy sources such as solar, wind, hydro and biomass, which can help reduce greenhouse gas and fossil fuel consumption. The volatile generation of renewable sources caused significant issues for traditional electricity transmission networks, which had been built to support centrally based and predictable power generation. The establishment of smart electrical network was finally indispensable to facilitate the high proportion of renewable energy into the existing power grid and preserve its stability, reliability and efficiency (Kabeyi & Olanrewaju, 2023; Kataray et al., 2023). Current developments and innovations in digital communication technologies, along with intelligent sensors and automated control systems, allowed the modern power grid to become more adaptive and responsive to varying energy demands.

The concept of a smart electrical network (SEN) combined information and communication technologies (ICTs) with the existing power system to allow real-time monitoring, decision-making processes and two-way energy flows. These features included boosting the management of distributed energy resources and increasing operational flexibility needed for integration of renewables. Smart grid technologies boosted power system resilience by enhancing the optimisation of processes used for the generation, transmission, distribution, and use of electricity (Ohanu et al., 2024). AI and machine learning applications also proved to be significant enablers for smart electrical

network integration with renewables. There were greater improvements in load forecasting, renewable generation forecasting, fault detection, and energy storage management using advanced analysis algorithms. By incorporating AI-driven optimization methods, grid reliability was strengthened to tackle the uncertainties of renewable energy sources, such as fluctuations in generation, and consumer demand, such as variability in demand. This study has optimized the grid performance by utilizing AI optimization techniques for addressing unpredictable renewable energy generation and consumer demand. (Talaat et al., 2023; Gangwar et al., 2024)

While significant advances in technology, there were still a number of obstacles to effective penetration of renewables into smart electrical networks. Stability of the electric power grid, capacity limitations, cybersecurity, lack of infrastructure development funding, and regulatory obstacles hampered sustainable energy transition programs. With the growing share of distributed renewable generation, innovative power system approaches that can tackle technical and operational challenges over a multitude of interconnected power systems became necessary (Ahmad et al., 2023; Kataray et al., 2023).

Background of the Study

Over the past decade or so, renewable energy systems have come on the scene as more people have become aware of the importance of the environment and the global climate agreements reached by the nation's leaders. Strategies to combat carbon emissions around the world drove a strong build-out of renewable energy infrastructure and sustainable power systems. There was thorough investment in renewable energy infrastructure and sustainable power technologies, driven by global efforts to curb carbon emissions. Soaring technology costs and strong government policies

drove extraordinary growth in solar PV and wind energy systems. With the rising HYGIENE penetration, operational problems such as generation intermittency, voltage fluctuations, frequency instability, network congestion, emerged (Kabeyi & Olanrewaju, 2023).

Conventional power generation had a centralised design, where the electricity generation followed a predictable pattern from large power generations. These types of systems were unable to be flexible enough to efficiently integrate distributed RE sources. Smart electrical networks appear as a viable solution, as they provide a technological solution for the incorporation of advanced communication systems, automation technology and digital monitoring tools with electricity networks. Smart grids facilitated the collection and control of the data in real-time which gave visibility of the operation and it added to the decision-making process on power networks (Ohanu et al., 2024).

The need to solve the problem of intermittent renewable generation and/or low electric reliability increased the relevance of energy storage systems. With battery storage the excess electricity produced during peak renewable generation times could be stored and used during low generation times. Energy storage solutions in smart electrical networks were suggested to increase the penetration rate of renewable energy resources and improve the power quality and flexibility of the grid (Ahmad et al., 2023). New technologies lately also facilitated the incorporation of AI, deep learning and predictive analytics into power system operations. These technologies helped boost renewable energy forecasting, optimise energy dispatch decision and enhance fault diagnosis mechanisms (Talaat et al., 2023; Gangwar et al., 2024).

Research Problem

The electricity generation system has changed significantly due to growing share of renewable energy resources, but linking these resources with mature and established electrical system still was a big challenge. Energy sources which were renewable were characterized by varying and intermittent nature of their generation patterns, contributing operational uncertainties and stability concerns in energy power systems. Typical grid architectures were hard to implement when integrating a high share of renewables in a flexible, intelligent and adaptive manner with systems control functions. The reliability, quality of energy delivered and efficient distribution of energy over the grid was a challenge for the utilities and energy planners.

Research Objectives

1. To examine the role of smart grid technologies in renewable energy integration.
2. To evaluate the influence of energy storage systems on sustainable energy transition.
3. To assess the contribution of demand-side management strategies to smart electrical network performance.

Research Questions

- Q1. How did smart grid technologies influence renewable energy integration?
- Q2. What effect did energy storage systems have on sustainable energy transition?
- Q3. How did demand-side management strategies contribute to smart electrical network performance?

Significance of the Study

This research added to the existing knowledge base on integrating renewable energy sources and designing smart electrical networks, featuring advanced methods and technologies that aided sustainable energy change. The outcomes were important in the theoretical knowledge that covers the correlation between the use of smart grid technologies, energy storage systems, energy

management on the energy demand side and the integration of renewable energy technologies based on artificial intelligence. The study filled the gaps in current literature on the effect of the simultaneous application of these technological solutions in a power system. The study provided policy guidance for policy makers, power companies, energy planners and technology developers to support the development and deployment of renewables and enhance the efficiency of the electric network. The results helped decision makers to identify better ways to improve the reliability of the grid, reduce operating costs and meet sustainability goals.

Literature Review

Smart Grid Technologies and Renewable Energy Integration

The smart grid technologies became a key enabling technology for renewable energy integration, as they contributed to a more flexible, intelligent and responsive power system. Traditional electric power lines were particularly hard hit by the fluctuating and unpredictable nature of renewable energy, researchers noted. Smart grids solved these problems in several ways: by incorporating advanced sensing technology, by introducing automated control systems, and by implementing real-time communication channels that enhance the visibility and efficiency of the grid. When digital technologies are incorporated into the power networks, it facilitated the utilities to optimize energy distribution in power networks, minimize transmission losses, and enhance the system reliability during the dynamic operating condition (Hassan et al., 2023; Javaid et al., 2023).

In recent studies, smart grid architectures have been suggested as a way to enable the widespread implementation of DRES. Smart grids enabled efficient energy usage and allow electricity generation to be distributed and involve consumers as active producers. The incorporation of advanced

metering infrastructure and the Internet of Things (IoT) enabled technologies enhanced data collection and demand forecasting capabilities, thereby enhancing stability and operational performance of the grid. The implementation of smart grids was found to have a significant role in reducing carbon emissions and promoting sustainable energy use across a number of areas, including the better utilization of renewable energy sources (Bedi et al., 2024; Khan et al., 2023).

Electrical networks became more complex, there was a greater need for adaptive management solutions. Smart grids were evolving with advanced technology such as predictive analytics, cloud computing and intelligent control algorithms for optimization of energy flow in the interconnected systems. These technologies offered better integration of solar and wind power generation by reducing fluctuations and guaranteeing a continuous power supply. Smart grid architectures increased the resilience and ability to coordinate distributed energy resources in a more sustainable and reliable energy system (Almalaq & Edwards, 2023; Sarker et al., 2024).

Energy storage systems and demand-side management

To overcome intermittency of renewable energy generation, energy storage systems have been playing an important role. As solar and wind energy shares gain traction, the demand for technologies to manage electricity supply and demand over time grows. BESS technology enabled a practical solution for the station by storing interrupted renewable energy when generation is high and when it was needed the most or at low generation intervals. The current study revealed that energy storage technologies (ESTs) facilitated the flexibility of the grid, optimized the utilization of renewable energy, and ensured greater reliability

of the power system in smart electrical networks (Akinyele & Rayudu, 2023; Arani et al., 2024).

Demand Side Management became one solution to enhance energy efficiency and energy integration through renewable energy. Demand responsiveness programs aimed at convincing customers to change their use of electricity according to a real-time price signal and other grid characteristics. These schemes eased peak demand pressures and made use of renewable energy resources in a more efficient manner. Operational efficiency and energy cost and greenhouse gas emission reductions were proven as beneficial outcomes of the decision-making process used in implementing DSM in smart grid environments (Mwasilu et al., 2023; Vardakas et al., 2023). Smart energy management platforms linked storage resources to demand response, to help balance energy usage and production. The integrated approach enhanced the overall performance of the network and helped to shift toward low-carbon electricity generation systems to accommodate the growing share of renewables in the grid (Mohandes et al., 2024; Ahmad et al., 2024).

Artificial Intelligence and Advanced Power System Optimization

AI revolutionized the operation of modern power systems, providing intelligent decision-making processes and predictive analytical capabilities. The use of AI algorithms increased the accuracy of wind, solar, and hydro energy forecasting, empowering system operators to better predict energy supply and demand changes. Power system operating efficiencies improved due to AI-powered algorithms and greater accuracy in wind, solar and hydro energy forecasting. To detect the pattern, optimize the energy dispatch, and resources over smart electrical networks, the operational data quantity had been leveraged by machine learning models. The researchers also pointed out that AI

applications in Power Systems have been crucial for enhancing the reliability and efficiency of power systems under renewable energy conditions (Rathore et al., 2024; Hossain et al., 2023).

Predictions were not the only applications that saw new AI developments; others included fault detection, predictive maintenance, and grid security management. These disruptions were minimised thanks to the use of machine learning algorithms to deliver predictive maintenance and potential problems with the equipment detected before they happen, combined with advanced models of deep learning. AI-based control systems also enhanced distributed energy resources' performance through dynamic control of energy flows in response to network changes. By enabling better system resilience and enhancing the ability of a smart electrical grid to integrate renewable energy generation, these technological advancements played a significant role in meeting the growing demand for sustainable power sources. The technological developments have made smart electrical networks more resilient and enhanced the capability of integrating renewable energy signals within the grid since the increasing need for sustainable energy sources (Khan et al., 2024; Ali et al., 2023).

The literature of recent years highlighted how AI was a strategic catalyst for the energy transition towards sustainable systems, partly by acting as a tool for managing the grid without supervision and real-time optimization. Energy management systems employing AI and technologies improved the synchronization of renewable energy supplies, storage solutions, and consumer demand. These systems enhanced decisions making precision and sped up the growth of self-healing smart grids with the ability to respond to operational faults without human intervention (Sharma et al., 2024; Kumar et al., 2023).

Research Methodology**Research Design**

In order to comprehend the impact of advanced power system techniques to integrate renewable energy resources in smart electrical networks, this study employed a quantitative research design. In order to facilitate the study of sustainable energy transition within the study area, the quantitative approach was selected to guarantee that the numerical data related to smart grid technologies, energy storage systems, demand side management, and artificial intelligence-based optimization of energy and water systems were collected and analyzed in a methodical manner.

Population of the Study

The target population included professionals in the electricity utilities, renewable energy sector, electricity smart grid management sector, power system engineering firms and energy regulation sector. These people had the requisite knowledge and practice in the integration of renewable sources and smart electrical network operation. Participants consisted of energy planning/energy system management policy makers, renewable energy consultants, grid operators, energy managers, engineers and technical specialists.

Sample Size and Sampling Technique

For this study, the researchers chose a sample size of 320 respondents. This was considered to be adequate to permit more sophisticated statistical analyses and to ensure the reliability of the results. Purposive sampling technique was used as the respondents were chosen due to their knowledge and experience in renewable energy projects and operations of smart electrical networks. The purposive sampling method helped to ensure that participants have a good understanding of the research topic and are able to answer the research questions with informed answers about advanced

power system strategies and sustainable energy transition.

Data Collection Instrument

Based on the literature from current sources on demand side management, energy storage systems, smart grids, renewable energy integration, and AI use in power systems, a structured questionnaire was created. This questionnaire was used to gather the primary data. The questionnaire was divided into two pieces. Gender, age, education, professional experience, and organizational affiliation were among the demographic profile data in the first section. Multiple item constructions were used to measure the study variables in the second section. Every item was evaluated using a Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). The questionnaire was created to guarantee uniformity and facilitate quantitative analysis of the answers.

Measurement of Variables

Demand-Side Management, Artificial Intelligence Based Optimization, Energy Storage Systems, and Smart Grid Technologies were chosen as the independent variables. Quantifying the effectiveness of intelligent communication, automation, and monitoring systems in electric networks was the goal of smart grid technologies. The significance of energy storage technologies in balancing the supply and demand of renewable energy was assessed by Energy Storage Systems. Demand-Side Management took into account load management strategies that would increase grid efficiency as well as the level of customer involvement. Artificial Intelligence Based Optimization used forecasting, control, and decision-making to determine how AI affected power network performance. The level of advanced power system strategies supporting renewable energy integration, energy efficiency, grid reliability and environmental sustainability was measured

using Sustainable Energy Transition as the dependent variable.

Data Collection Procedure

Data collection was done by e-mailing and mailing questionnaires to professionals involved in relevant energy sector organizations. The purpose of the study was explained to the respondents and they were assured of confidentiality and anonymity of their responses. It was a voluntary participation and respondents gave informed consent to fill the questionnaire. Data collection was continued until 320 valid responses were obtained.

Data Analysis Techniques

A Statistical Package for Social Sciences (SPSS) version 29 was used to analyze the collected data. The characteristics of the respondents and the distribution of variables were described using descriptive statistics, including frequency, mean,

standard deviations, and percentages. The correlations between the research variables were investigated using a Pearson correlation. To determine how Smart Grid Technologies, Energy Storage Systems, CSS, and Demand-Side Management affect the Sustainable Energy Transition, a multiple regression approach was used. To aid in the comprehension of the results, tabular and graphical (bar charts) presentations of the statistical significance were carried out at the 95% significance level.

Results and Analysis

Demographic Profile of Respondents

The demographic analysis gave an overview of the characteristics of the respondents, and ensured the suitability of the sample for the examination of renewable energy integration in smart electrical networks.

Table 1: *Demographic Characteristics of Respondents (N = 320)*

Demographic Variable	Category	Frequency	Percentage (%)
Gender	Male	208	65.0
	Female	112	35.0
Age	25-34 Years	86	26.9
	35-44 Years	128	40.0
	45-54 Years	72	22.5
	Above 54 Years	34	10.6
Education	Bachelor's Degree	84	26.3
	Master's Degree	171	53.4
	Doctorate Degree	65	20.3
Experience	Less than 5 Years	63	19.7
	5-10 Years	129	40.3
	11-15 Years	78	24.4
	More than 15 Years	50	15.6

The demographic exam found that male respondents accounted for 65.0% of the total respondents and female respondents accounted for 35.0% of the total respondents. The data indicated

that the industry of energy and power systems was still largely male dominated, with an occasional place given to the participation of women. Gender balance helped to bring in a diversity of

perspectives with regard to integration with renewals and the management of a smart electric network. As observed from the age profile presented above, the highest frequency observed was for the age group of 35-44 yrs (40.0%). This finding shows that the participants possessed the relatively experienced background knowledge and technical skills which facilitate their study. The largest age group was aged 25 to 34 years (26.9%), followed by old age group of 45 to 54 years (22.5%).

10.6% of the sample was over 54 years old. It was observed that 53.4% of the participants had Masters degree, 26.3% reached to the Bachelor's level and 20.3% achieved the doctorate level. Results indicated that the sample had a high level of education and education that enabled them to base their views on the advanced power system strategies and the energy sector transition towards sustainability.

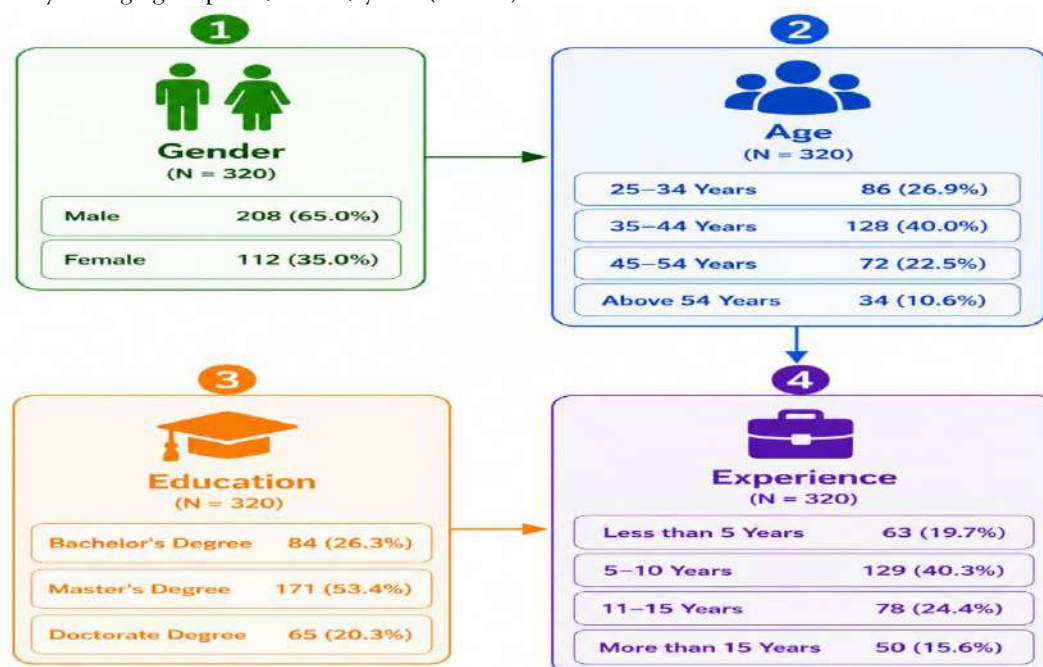


Figure 1. Demographic Characteristics of Respondents (N = 320)

Descriptive Statistics of Study Variables

Descriptive statistics were conducted to evaluate respondents' perceptions regarding Smart Grid

Technologies, Energy Storage Systems, Demand-Side Management, Artificial Intelligence-Based Optimization, and Sustainable Energy Transition.

Table 2: Descriptive Statistics of Study Variables

Variables	Mean	Standard Deviation
Smart Grid Technologies	4.21	0.58
Energy Storage Systems	4.16	0.61
Demand-Side Management	4.08	0.65
Artificial Intelligence-Based Optimization	4.29	0.55
Sustainable Energy Transition	4.25	0.57

The descriptive results revealed very high means in all the power system variables, indicating that all the advanced power system strategies that the respondents considered were of very high importance. The highest mean, 4.29, was for Artificial Intelligence Based Optimization, showing an even better outlook from respondents and demonstrating that AI technologies are part and parcel of today's smart electrical networks. The mean score in Sustainable Energy Transition was 4.25, suggesting positive perceptions of how effective present technologies and policies are for

the environmental domain and uptake of renewables. Smart Grid Technologies received a relatively high mean value (4.21), indicative of its acceptance in the field of smart energy management and the ability to keep energy supply reliable. The somewhat small standard deviations values (0.55-0.65) showed that the opinions of the respondents were consistent. The results showed that the technology innovation has significant importance in making renewable energy integration easy and increase the performances of power system among professionals.

Smart Energy Variables: Mean Score Comparison

Values represent the mean and standard deviation of each variable

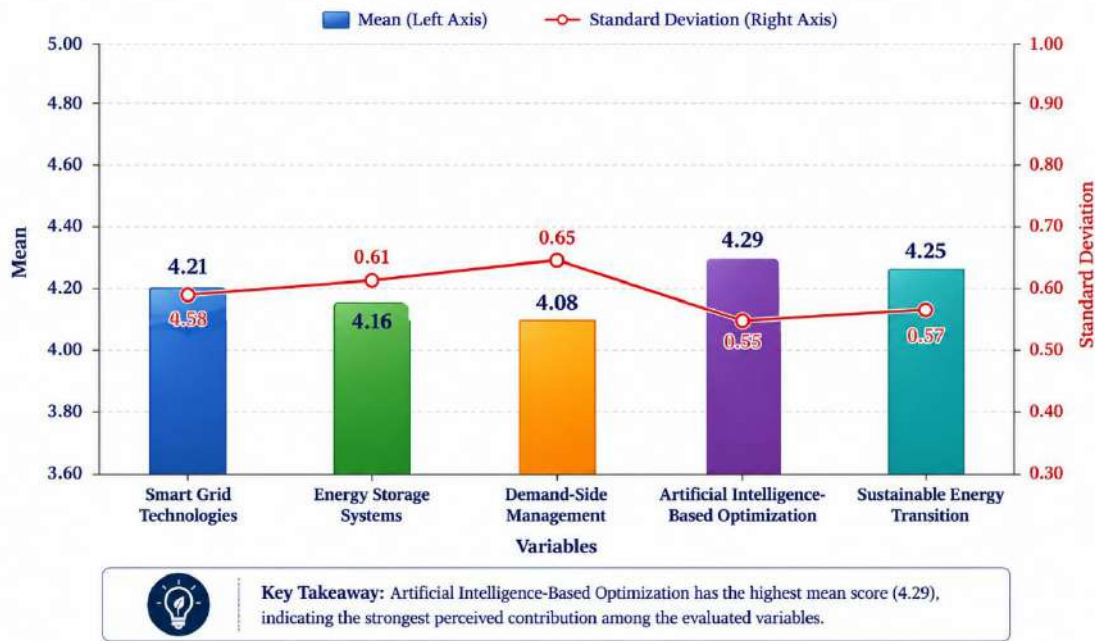


Figure 2. Descriptive Statistics of Study Variables

Correlation Analysis

Pearson correlation analysis examined the relationships among the independent variables and Sustainable Energy Transition.

Table 3: Correlation Matrix of Study Variables

Variables	1	2	3	4	5
1. Smart Grid Technologies	1				
2. Energy Storage Systems	0.621	1			

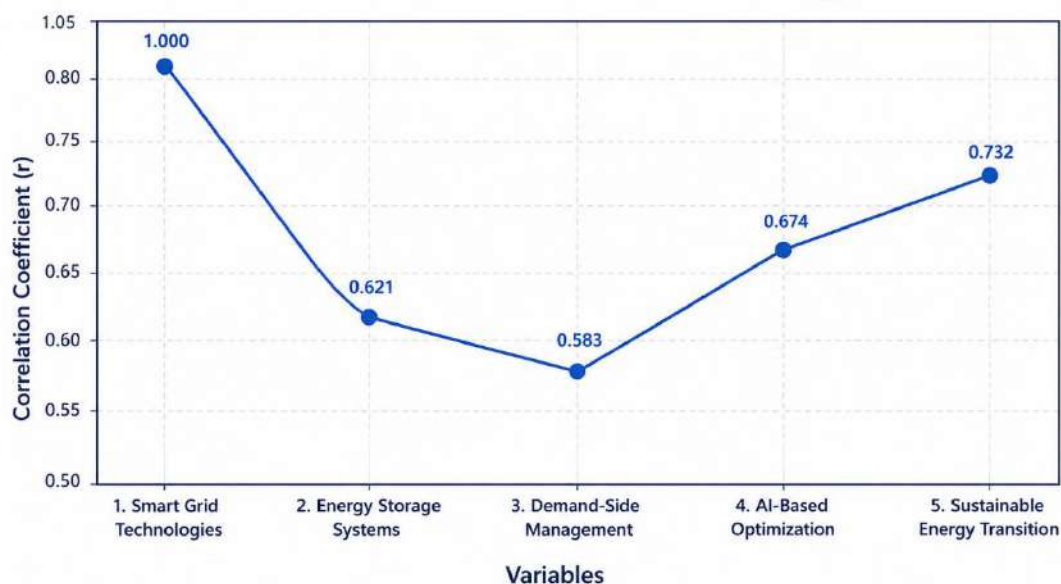
Variables	1	2	3	4	5
3. Demand-Side Management	0.583	0.596	1		
4. AI-Based Optimization	0.674	0.648	0.611	1	
5. Sustainable Energy Transition	0.732	0.698	0.653	0.781	1

Note: $p < 0.01$

Correlation results showed that the correlation between all the study variables are positive and significant. Smart Grid Technologies had a positive association with Sustainable Energy Transition ($r = 0.732$, $p < 0.01$), signifying that advancements in the smart grid space had improved improvements in sustainable energy goals. The positive correlation coefficient (0.698) for Energy Storage Systems and Sustainable Energy Transition indicates that energy storage technologies played a significant role in the

integration of renewables and ensuring energy network stability. Demand Side Management also showed a very strong positive correlation with the dependent variable ($r = 0.653$; $p < 0.01$). Artificial Intelligence Based Optimization had the highest correlation with Sustainable Energy Transition ($r = 0.781$, $p < 0.01$). The outcome indicated that Aided Forecasting, optimization, with controlling mechanisms is critical in improving smart electrical networks' efficiency and sustainability.

Correlation of Variables with Sustainable Energy Transition



Note: Values represent Pearson correlation coefficients (r). All correlations are positive and significant.

Figure 3. Correlation Matrix of Study Variables

Multiple Regression Analysis

Multiple regression analysis assessed the influence of Smart Grid Technologies, Energy Storage

Systems, Demand-Side Management, and Artificial Intelligence-Based Optimization on Sustainable Energy Transition.

Table 4. *Regression Results*

Predictor Variables	Beta (β)	t-value	p-value
Smart Grid Technologies	0.341	7.92	0.000
Energy Storage Systems	0.298	6.84	0.000
Demand-Side Management	0.267	5.97	0.000
Artificial Intelligence-Based Optimization	0.385	8.76	0.000

Table 5. *Model Summary*

R	R ²	Adjusted R ²	F-value	Sig.
0.833	0.694	0.690	178.52	0.000

The regression results showed that all the predictor variables have significant effects on Sustainable Energy Transition. An influential factor was 'Artificial Intelligence Based Optimization' (AIBO) ($\beta = 0.385$, $p < 0.001$), which accounted for a substantial increase in the uptake of AI tools for forecasting energy production, optimizing consumption, and making predictions and decisions. Smart Grid Technologies had a beta coefficient of 0.341, making it the second best predictor. The results showed that the communication infrastructure, automation systems, real-time monitoring areas impacted significantly in sustainable energy. Energy Storage Systems also positively influenced the study with a significant value ($\beta = 0.298$), indicating the importance of these systems in managing system intermittency

and ensuring its reliability. Solutions for sustainable energy transition (beta coefficient: 0.267) were positively influenced by Demand-Side Management. The model explained 69.4% of the variance of Sustainable Energy Transition, as demonstrated by the R square value, with the independent variables; Incentive package, Technology, Strategy, and Leadership. The F-value of the overall regression model was significant ($F = 178.52$; $p < 0.001$), thus giving credit to the overall strength of the regression model and the predictive ability. The results showed that the advanced power system methods were all important factors in aiding renewable energy integration and in aiding to power system transition towards sustainable electrical networks.

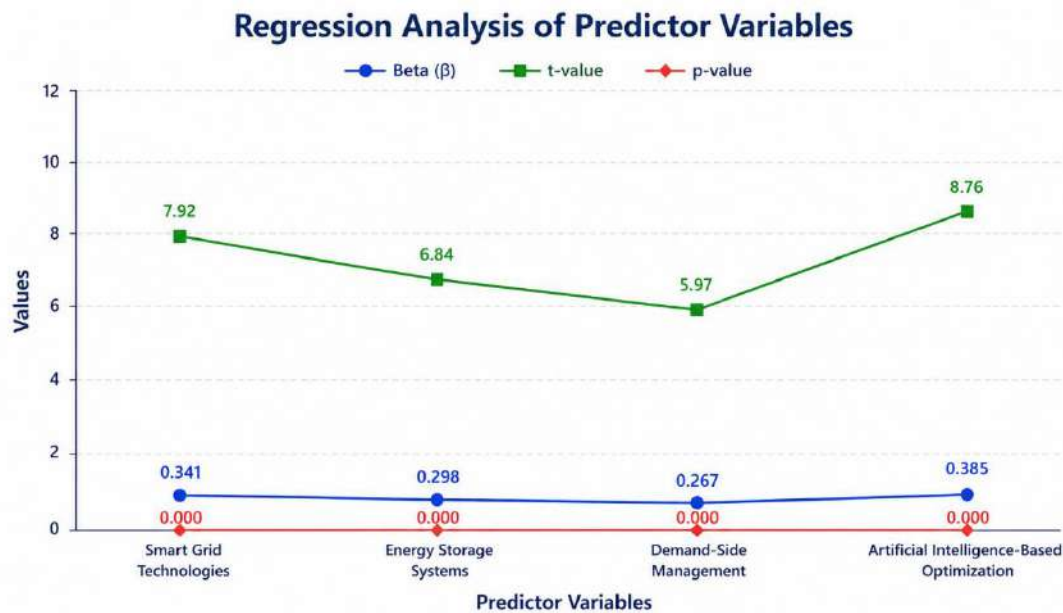


Figure 4. Regression Results

Discussion

The study revealed that utilizing advanced strategies for power systems played a significant role in the integration of renewable energy resources and the transition towards a more sustainable energy system in smart electrical networks. When analyzing the regression results, AI-based optimization was found to be the most important factor determining sustainable energy transition, suggesting the improvement of the network's performance and overall efficiency when using data-driven decision making systems, automated control mechanisms and intelligent forecasting. The results were consistent with the studies recently carried out, which highlighted how artificial intelligence can contribute to optimizing the production of renewable energy, to manage energy efficiency, and enhance the flexibility of the electrical network, facing the uncertainty conditions in its operation (Liu et al., 2024; Abdel-Basset et al., 2023). Natural intelligence was a dominant theme indicating that the modern power system campaigned more and more on predictive analytics and machine learning techniques to

overcome challenges of renewables variability and demand fluctuations.

The findings also demonstrated that the smart grid's technologies significantly aided the shift to sustainable energy. When linked into electrical networks, intelligent communication systems, sophisticated metering infrastructure, and real-time monitoring capabilities were proven to enhance the reliability of renewable energy sources. The findings were consistent with earlier research that found the smart grid is a crucial component of sustainable energy systems because of its contributions to operational effectiveness, dependability, and bidirectional energy supply and demand between producers and consumers (Alotaibi et al., 2023; Hossain et al., 2024). The results indicated that, with smart grid technology in place, energy companies could use better control of DRS and maintain stability and reduce transmission loss.

Energy storage systems also showed that they played a major role in transitioning to sustainable energy. Positive impact—it's helpful whenever the electricity generated by solar and wind power is not

consistent. Energy storage systems provided resilience to the grid by storing excess energy when it is being generated and releasing it when it is most needed, while helping to increase the use of renewable energy. This finding was congruent with previous research which emphasized battery storage systems as vital components for integral renewable energy integration due to their positive impacts on power quality, frequency regulation and operational reliability within the modern electro networks (Koochi-Fayegh & Rosen, 2024; Zhang et al., 2023). Based on the results presented, it was concluded that energy storage technologies were of key importance as a balancing technology between electricity supply and demand for more distributed energy systems.

Another aspect the study examined that had a positive effect on sustainable energy transition was demand side management. The strong correlation between the target variable and demand side management suggests that consumers' involvement and good load management practices enhanced overall network efficiency. Demand response programs incentivized users to modify their electricity usage based on grid demand and conditions, including requesting variable shifts in usage and installing temporary loads when demand was low. Participation in DR programs included varying the timing of electricity load demand and placing temporary loads or requesting varying time periods of usage depending on the grid load demand. These results were consistent with recent research showing the promise of demand-side management (DSM) and demonstrating how it may improve energy efficiency, lower operating costs, and benefit the environment in smart energy systems (Yao et al., 2023; Alhelou et al., 2024). The results showed that a key element of future smart grid development initiatives is active customer interaction.

The model was able to explain a substantial amount of the variance in relation to SEN, indicating that combining these sophisticated power system strategies improved both the general performance of the electrical networks and the integration of renewable energy. This model's explanatory power also led to the increasing acceptance that coordinated implementation of smart grid technologies, artificial intelligence applications, energy storage systems and demand-side management programs was important for the successful launching of energy transition initiatives. James et al. (2023) and Notables et al. (2024) made similar findings in recent research, highlighting the need for integrated technological solutions to increasingly decarbonize economies while also enhancing energy security. The results indicated that investments in intelligent energy infrastructure and advanced digital technologies needs to be improved to stimulate sustainable energy transition, and to strengthen energy system resilience for the long-term, particularly by the energy planners, operators and policy makers.

Conclusion

In order to support the integration of renewable energy sources into smart electrical networks and the sustainable energy transition, the research in this thesis concentrated on advanced power system techniques. The findings demonstrated that important elements of demand-side management, energy storage systems, smart grid technologies, and artificial intelligence-based optimization significantly contribute to achieving the sustainable energy objective. The most important indicator of the sustainable energy transition was found to be Artificial Intelligence Based Optimization ($\beta = 0.385$), with values of 0.341, 0.298, and 0.267 for Smart Grid Technologies, Energy Storage Systems, and Demand-Side Management, respectively. The independent variables and the Sustainable Energy

Transition also showed strong positive correlations, underscoring the significance of technological innovation in improving grid operation, reliability, and the usage of renewable energy. Power system techniques are important in contemporary energy systems; the regression model explained 69.4% of the variance in the sustainable energy transition ($R^2 = 0.694$).

Recommendations

The sources of the research also reveal that more energy should be invested in smart grid infrastructure with respect to communication, monitoring, and automation in electrical networks. There should be more advanced metering and digitizing of control systems and technologies implemented throughout utilities to optimize use of available systems and to allow integration of renewable energy sources. More investment is needed in large-scale energy storage systems, including batteries, and other energy storage solutions to help mitigate intermittently deployed renewable energy resources and enhance grid stability. The use of the applications of artificial intelligence should be further promoted to enable prediction of maintenance, prediction of load, prediction of renewable generations and real-time decision making processes. Energy demand-side management programs should be reinforced by consumer awareness programs, dynamic pricing and energy conservation programs to further incentivize participation. There should be greater joined problem solving between governments, utility providers, technology developers and research institutions for developing supportive governments regulations and moving the initiatives on sustainable energy transition forward.

Future Directions

Other technological elements that can have an impact on the integration of renewable energy should be explored in future research: blockchain-

based energy management systems, digital twins, edge computing and smart grid cybersecurity measures. To evaluate the diverse differences, comparative studies on smart grid deployment outcomes and renewable energy integration methodologies should be conducted globally. Longitudinal research designs can provide long-term insights into how such sophisticated power system innovations affect grid resilience and the sustainable energy transition. Lastly, it is important to research the long-term effects of integrating renewable energy from a range of stakeholders across different economic, social, and environmental factors. Research on larger and more representative samples could improve the results' generalizability and deepen our understanding of sustainable energy development in evolving smart electrical network environments.

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