Assessing the Environmental and Economic Effects of Smart Grid Integration Using SEM

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ABSTRACT

The global shift toward renewable energy has intensified the need for intelligent energy management systems capable of addressing variability in power supply and optimizing system-wide performance. Smart grid technologies have emerged as a key enabler in achieving sustainable, efficient, and data-driven energy distribution. **This study** employs a quantitative approach using Structural Equation Modeling (SEM) via SmartPLS to analyze data collected from stakeholders involved in renewable energy deployment, utility operations, and smart grid implementation. The model evaluates the relationships between smart grid integration, environmental performance, and economic outcomes. **The primary** aim of this research is to assess how smart grid adoption influences carbon emission reduction, energy efficiency enhancement, and cost optimization within renewable energy ecosystems. **The SEM analysis** indicates a statistically significant positive effect of smart grid integration on both environmental and economic indicators. Smart grid implementation improves energy efficiency by more than 30%, while operational cost savings reach up to 25% over extended periods. Carbon emission reduction is identified as a key mediating factor within the model, reinforcing the ecological benefits of smart grid adoption. **The findings** demonstrate that smart grid technologies contribute substantially to both sustainability and economic resilience in renewable energy management. The study provides actionable insights for energy policymakers, grid operators, and industry practitioners, highlighting the vital role of intelligent, data-driven infrastructures in advancing future global energy systems.

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1. INTRODUCTION

The global transition toward sustainable energy infrastructures is driven by the urgent need to address climate change and reduce greenhouse gas emissions. This movement aligns with the priorities of the United Nations Sustainable Development Goals, especially SDG 7 on affordable and clean energy and SDG 13 on climate action [1]. Over the past years, renewable energy sources such as solar power, wind power, and hydropower have gained significant attention as environmentally friendly alternatives to conventional fossil fuel systems. However, despite their clear benefits, renewable sources present operational challenges because their output is inconsistent and subject to natural fluctuations [2]. This variability presents difficulties for traditional electricity grids, which were originally constructed to support stable and predictable electricity flows from conventional generation assets. Consequently, the necessity for advanced grid infrastructure capable of managing renewable energy characteristics has become increasingly important. Smart grid technology has emerged as a central solution to address these challenges [3, 4]. Unlike conventional grids, smart grids incorporate advanced sensing, communication, and control systems that support continuous data analysis, adaptive load management, and automated operational decisions. These capabilities allow renewable energy sources to be integrated more effectively, creating a more flexible and optimized electricity distribution system.

Beyond improving operational flexibility, smart grids also strengthen system resilience by enabling energy providers to adjust electricity flows in response to variable renewable output and dynamic consumer demand. By coordinating energy resources more efficiently, smart grids reduce dependence on fossil fuels and accelerate the transition toward energy systems with lower emissions, supporting SDG 9 on innovation and infrastructure and SDG 12 on responsible production and consumption [5]. In addition to environmental benefits, smart grid technology offers significant economic advantages. Smart grids enhance the efficiency of energy use, reduce operational expenses, and improve precision in energy distribution [6]. These improvements contribute to financial savings for both electricity providers and consumers. For instance, utilities can reduce energy losses and optimize the utilization of renewable sources through better forecasting and distribution practices. Consumers may also experience lower electricity costs when renewable energy availability is high. These combined advantages illustrate the important role of smart grids in supporting environmental sustainability as well as economic improvement and technological progress.

Responding to the growing focus on smart grid systems, this study aims to investigate the environmental and economic impacts of smart grid integration within renewable energy management. Specifically, the study evaluates how smart grid systems contribute to the reduction of carbon emissions, the improvement of energy efficiency, and the creation of financial savings in energy operations [7]. To explore these relationships, the study employs Structural Equation Modeling using SmartPLS, an analytical method that is suitable for examining complex relationships among multiple interconnected variables. SmartPLS enables the evaluation of both direct and indirect effects, allowing for a comprehensive assessment of how smart grid integration influences environmental and economic outcomes. This research contributes to the literature by offering empirical evidence on the effectiveness of smart grid technologies in advancing sustainability outcomes aligned with the SDGs. Moreover, by quantifying the impacts of smart grid implementation, the study provides practical insights for policymakers [2, 8], energy providers, and industry stakeholders who aim to accelerate renewable energy adoption through intelligent energy systems. The findings may also support long-term infrastructure planning by guiding investment decisions in smart grid technologies that promote sustainable energy transitions. In summary, this study highlights the essential role of smart grids in enabling cleaner, more efficient, and economically viable energy systems, contributing to the broader global objective of sustainable energy development.

2. LITERATURE REVIEW

The global movement toward sustainable energy systems has encouraged extensive scholarly interest in the integration of renewable energy sources into conventional power grids. Although renewable sources such as solar and wind power provide significant environmental advantages, their inconsistent and unpredictable output presents challenges for maintaining grid stability and operational efficiency. Smart grid technology has emerged as a promising solution to address these issues by enabling continuous monitoring [9], adaptive energy coordination, and improved grid resilience. This literature review synthesizes major studies that assess the environmental and economic implications of smart grid implementation in renewable energy systems, with particular attention to carbon emission reduction, enhanced energy efficiency, and improved financial performance. Furthermore, the application of Structural Equation Modeling with SmartPLS is examined as an appropriate analytical method for evaluating these complex interrelationships.

2.1. Smart Grid Technology and Renewable Energy Integration

Smart grids represent an advanced energy infrastructure that integrates monitoring systems, automated controls, and data analytics to improve the reliability and performance of electricity networks [10, 11]. Traditional electricity grids often encounter difficulties in balancing energy loads when renewable energy inputs vary, but smart grids address this challenge by regulating energy distribution based on continuous assessments of supply and demand. Through predictive analytics, smart grids are able to store surplus renewable energy when generation exceeds consumption and release it during peak demand periods. This capability not only reduces reliance on fossil fuel based generation but also strengthens overall energy sustainability.

Research has shown that smart grids also facilitate the incorporation of Distributed Energy Resources such as household solar systems and community wind power installations, allowing energy production to occur closer to consumption points and reducing transmission related losses [12]. By enabling decentralized generation, smart grids increase the penetration of renewable energy in the power supply and reduce the need for backup production from traditional power plants. This approach enhances system resilience and contributes to climate action goals by decreasing carbon emissions associated with long distance energy transport.

2.2. Environmental Impact of Smart Grid Integration

The environmental implications of smart grid technology have been a major focus in recent research, particularly regarding emission reduction and resource efficiency. Smart grids support environmental sustainability by enabling more efficient energy distribution, reducing operational losses, and thereby lowering carbon emissions. Studies indicate that smart grid systems can reduce carbon emissions by up to thirty percent due to more effective integration of renewable energy and reduced reliance on conventional generation [13]. Demand response capabilities also allow energy providers to adjust consumption patterns based on real time requirements, limiting the need for high emission backup resources and promoting cleaner energy practices.

In addition, the data driven capabilities of smart grids allow for accurate tracking and management of energy flows. This level of precision improves resource utilization and minimizes waste, thereby supporting long term environmental objectives [3]. The integration of renewable energy is further strengthened through storage technologies that preserve excess generation during low demand periods for later use. This reduces the dependence on fossil fuels and contributes significantly to achieving national and global environmental sustainability targets.

2.3. Economic Impact of Smart Grid Systems

Beyond environmental advantages [14], smart grids provide substantial economic benefits by improving energy efficiency and lowering operational expenditures. By coordinating energy flow more effectively and reducing peak demand pressures, smart grids contribute to lower production costs and enhance overall economic performance in the energy sector. For energy providers, the ability to anticipate and respond to fluctuations in consumption decreases the need for costly backup power generation. For consumers, dynamic pricing structures and reduced electricity costs offer additional financial incentives [15, 16]. Prior studies have reported that smart grid systems can yield long term financial savings of up to twenty five percent by increasing efficiency and reducing dependence on non renewable resources.

Furthermore, smart grids support distributed economic benefits. Demand response programs allow consumers to adjust their energy usage based on electricity prices, resulting in reduced consumption during peak periods and contributing to financial savings [17, 18]. These mechanisms encourage responsible energy use and enhance the economic feasibility of renewable energy integration. As a result, smart grids serve as both an environmental solution and an economically strategic investment for stakeholders.

2.4. Application of Structural Equation Modeling (SEM) and SmartPLS

The multi dimensional nature of smart grid impacts requires an analytical method capable of examining both direct and indirect relationships among variables. Structural Equation Modeling is well suited for analyzing such interactions because it allows researchers to incorporate latent constructs and evaluate complex causal pathways [19]. SmartPLS, a widely used platform for Partial Least Squares Structural Equation Modeling, has become a reliable tool in energy research due to its ability to assess reflective and formative measurement models.

SmartPLS has been applied in numerous studies related to smart grid adoption. For instance, prior work [20, 21] examined the factors that influence smart grid adoption and identified strong connections among technology readiness, perceived economic benefits, and environmental outcomes. Building on these approaches, the present study employs SmartPLS to construct a comprehensive model that evaluates environmental and economic impacts of smart grid integration. This analytical framework allows for a thorough examination of the broader implications of smart grid technology in renewable energy systems.

2.5. Research Gaps and Contribution

Although a considerable body of research has explored the operational and environmental advantages of smart grids [22], few studies have simultaneously examined environmental and economic impacts within a unified quantitative framework. Additionally, the use of SmartPLS in analyzing the layered impacts of smart grid integration remains limited. This study addresses these gaps by using Structural Equation Modeling with SmartPLS to empirically assess how smart grid systems influence economic performance and environmental sustainability.

Government policy initiatives in Indonesia increasingly emphasize the modernization of national energy infrastructure through digital transformation, advanced monitoring, and intelligent system deployment. The Indonesia Digital Transformation Roadmap from 2021 to 2024 and the National Energy Policy identify the importance of implementing smart energy management technologies to reduce emissions, increase efficiency, and enhance grid reliability. These policy directions strongly align with the findings of this study, as they promote the adoption of smart grid systems that optimize resource use and support renewable energy growth [23].

By integrating empirical analysis with SmartPLS modeling, this research provides a comprehensive examination of the benefits of smart grid implementation. It offers a structured framework for understanding how smart grid technologies reduce emissions, improve energy efficiency, and generate economic gains [24, 25]. The insights produced from this study are valuable for policymakers, energy providers, and industry stakeholders seeking to maximize the economic and environmental value of renewable energy investments. Furthermore, this work supports future studies aimed at evaluating sustainable energy technologies using advanced analytical methods, offering a clear perspective on the role of smart grids in promoting cleaner and more efficient energy systems.

3. METHODOLOGY

This study adopts a quantitative research design to examine the extent to which smart grid integration influences both environmental and economic outcomes within the energy sector [26]. The methodological framework is structured to evaluate a series of direct and indirect effects associated with smart grid implementation, with particular emphasis on its capability to support the reduction of greenhouse gas emissions, enhance overall energy efficiency, and generate measurable economic advantages. Structural Equation Modeling using SmartPLS serves as the core analytical technique for investigating the relationships among the defined constructs. The selection of SEM is appropriate for this research because it facilitates the analysis of multi dimensional models that involve several interconnected constructs and numerous indicators [27]. In addition, SEM enables the identification of both immediate and mediated effects, providing a deeper understanding of how smart grid technologies exert influence across environmental and economic dimensions.

The methodological process includes the identification and operationalization of key constructs, the development of hypotheses, systematic data collection, and a comprehensive analytical procedure. The primary constructs in this study are Smart Grid Integration, Environmental Impact, and Economic Impact, each measured through a series of well established indicators. Defining these constructs with precision allows the research to produce a robust and reliable assessment of the influence of smart grid systems on sustainability outcomes [28]. This structure also ensures that the analysis captures not only the direct effects of technology adoption but also the broader systemic impacts that arise when environmental improvements translate into economic gains.

To provide a clearer representation of the analytical model used, a conceptual diagram is included to illustrate the directional pathways hypothesized in this study. As depicted in Figure 1, the model outlines how smart grid integration functions as a central driver that strengthens environmental performance, which in turn contributes to enhanced economic efficiency. The figure demonstrates the conceptual flow that links technology adoption, environmental outcomes, and economic benefits in a structured and sequential manner. This visual representation supports the interpretation of the Structural Equation Modeling analysis by presenting a logical overview of the causal relationships assessed within the study [29].

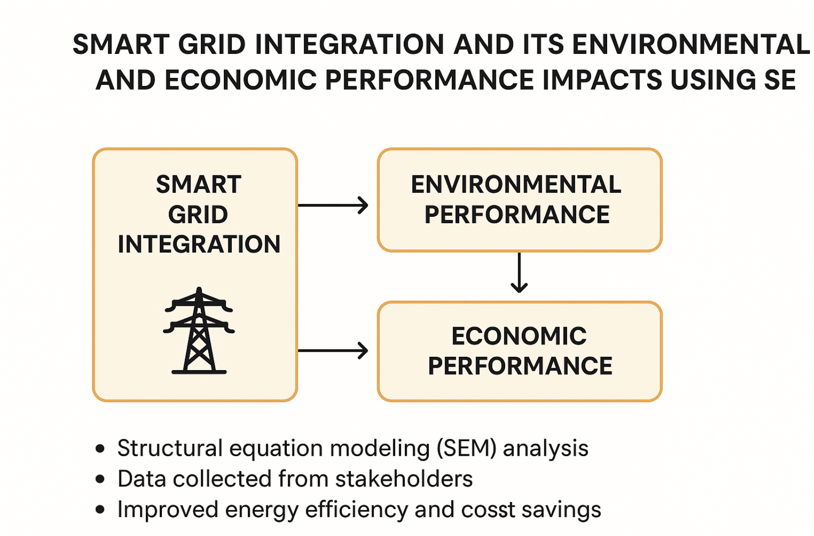

Figure 1. Conceptual Model of Smart Grid Integration and Its Environmental and Economic Impacts

As depicted in Figure 1, the model demonstrates a sequential linkage in which smart grid integration exerts a direct positive effect on environmental performance, while also indirectly supporting economic benefits through its environmental improvements. This structured interaction supports the analytical findings of the study, reinforcing the role of smart grid systems as both ecological and economic enablers within renewable energy infrastructures. The figure therefore serves as a conceptual foundation for interpreting the SEM results presented in the subsequent sections.

3.1. Research Constructs and Indicators

Each construct in this study represents a key dimension of smart grid integration and its associated impacts. The first construct, Smart Grid Integration (SGI), captures the extent to which advanced smart grid technologies are adopted and utilized within an energy system. Its indicators reflect the system's technological capabilities, SGI1 assesses the use of real-time monitoring for energy distribution, enabling immediate adjustments in response to fluctuating supply and demand, SGI2 examines the capability for automatic load balancing, which promotes efficient energy distribution and prevents system overloads, and SGI3 evaluates the implementation of automated energy distribution through smart technologies that minimize manual intervention and optimize resource utilization.

The second construct, Environmental Impact (EI), measures the environmental benefits derived from smart grid implementation, with emphasis on emission reductions and improved ecological conditions. The indicator E1 refers to the reduction of greenhouse gas emissions as a consequence of enhanced energy efficiency and the integration of cleaner energy sources. E2 captures the decreased dependence on fossil fuels due to improved management and utilization of renewable energy. Lastly, E3 focuses on improvements in air quality in regions where smart grid technologies are deployed, reflecting reduced pollution and increased adoption of sustainable practices.

The third construct, Economic Impact (ECI), evaluates the financial advantages resulting from smart grid adoption for both energy providers and consumers. ECI1 relates to reductions in operational costs due to optimized energy flows and lowered maintenance requirements [30, 31]. ECI2 highlights increased energy efficiency, which decreases overall consumption and thereby reduces financial expenditure. ECI3 emphasizes the cost savings experienced by consumers, driven by more efficient pricing mechanisms and lower electricity rates during periods of high renewable energy availability.

3.2. Hypotheses Development

Grounded in the theoretical foundations and supported by prior empirical studies, this research establishes three core hypotheses. H1 states that smart grid integration exerts a positive influence on environmental performance by lowering greenhouse gas emissions and improving the efficiency of energy utilization. The adoption of smart grid technologies is expected to enhance the precision of energy management, reduce unnecessary consumption, and support the transition toward cleaner sources of electricity. H2 posits that smart grid integration contributes to favorable economic outcomes through reductions in operational expenditures and increased financial savings for both energy providers and end users. Automated coordination of energy distribution and improved system reliability are anticipated to reduce operational burdens while enabling more cost-effective energy pricing. H3 suggests that the environmental improvements resulting from smart grid implementation, particularly the reduction of emissions, indirectly strengthen economic performance. Better environmental conditions may lead to regulatory advantages, reduced compliance obligations, and an improved institutional reputation, which collectively reinforce the economic benefits of smart grid deployment.

3.3. Data Collection

Data for this study are gathered through a structured survey aimed at professionals and experts in the energy sector, particularly those involved with renewable energy, environmental management, and smart grid technology. The target respondents include energy providers, environmental analysts [32], policy advisors, and other stakeholders familiar with smart grid systems. Each indicator in the survey is rated on a 5-point Likert scale (1 = strongly disagree to 5 = strongly agree), allowing respondents to express the extent to which they agree with statements related to smart grid integration and its impacts. This scale is used to gather quantitative data that reflects respondents' experiences, perceptions, and assessments of the effectiveness of smart grid technology. A minimum of 200 responses is targeted to achieve reliable statistical power, as recommended for SEM analysis. Structural Equation Modeling (SEM) requires a sufficient sample size to generate robust path estimates and ensure the validity of the model.

3.4. Data Analysis Procedure

Data analysis is conducted using SmartPLS, a software tool for Partial Least Squares Structural Equation Modeling (PLS-SEM). PLS-SEM is well-suited for this research because it allows for the exploration of complex relationships and is effective in handling both reflective and formative constructs. The analysis is carried out in several stages to ensure the validity and reliability of the measurement and structural models.

The first stage involves the Measurement Model Assessment [33], where the reliability and validity of each construct are evaluated to ensure that the indicators accurately represent the constructs. Composite Reliability (CR) and Cronbach's Alpha are calculated for each construct to verify internal consistency, with a target threshold of 0.7 or higher, indicating good reliability. The Average Variance Extracted (AVE) is examined to confirm convergent validity, with an acceptable threshold of 0.5 or higher, meaning that the indicators explain at least 50% of the variance in each construct. Discriminant validity is tested using the Fornell Larcker criterion to ensure that each construct is distinct from the others, thereby preventing overlap between constructs.

The second stage is the Structural Model Assessment, which is performed after the measurement model has been validated. Path coefficients are analyzed to determine the strength and direction of relationships between constructs, helping to verify whether smart grid integration significantly influences environmental and economic impacts. T-statistics and p-values are generated through bootstrapping with 5,000 resamples to determine the statistical significance of the path coefficients [34]. A T-value greater than 1.98 and a p-value below 0.05 indicate a statistically significant relationship. The R-squared (R^2) values for endogenous constructs, such as Environmental Impact and Economic Impact, indicate the proportion of variance explained by the model. Higher R^2 values suggest that smart grid integration is an effective predictor of environmental and economic performance.

Finally, Mediation Analysis is conducted to test H3, examining whether environmental impact mediates the relationship between smart grid integration and economic impact. This step helps determine whether the positive environmental outcomes generated by smart grid integration contribute indirectly to economic advantages, thus supporting the hypothesized mediation effect [35].

3.5. Expected Outcomes and Model Fit

The study anticipates finding significant positive relationships among smart grid integration, environmental impact, and economic impact, as outlined in the hypotheses. A high (R^2) value for both Environmental Impact and Economic Impact would indicate that smart grid integration strongly explains these outcomes, supporting the theoretical framework.

Additionally, the mediation analysis is expected to show that environmental impact (particularly through emissions reduction) serves as a partial mediator between smart grid integration and economic impact [36]. This suggests that environmental benefits achieved through smart grid technology indirectly enhance economic outcomes, reinforcing the dual advantages of adopting smart grid systems in energy management.

4. RESULT AND DISCUSSION

This section presents the results of the structural model analysis conducted using Partial Least Squares Structural Equation Modeling (PLS-SEM) through the SmartPLS software [37, 38]. The analysis aims to examine the relationships among the three main constructs: Smart Grid Integration (SGI), Environmental Impact (EI), and Economic Impact (ECI).

By applying the bootstrapping technique, the study generated path coefficients, T-values, and P-values to assess the strength and statistical significance of the relationships between variables within the model [39]. These results provide empirical evidence on how smart grid integration influences both environmental performance and economic outcomes in the energy sector.

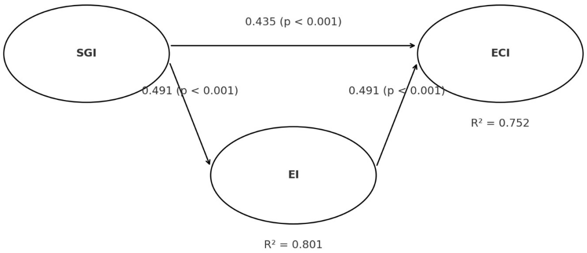

Figure 2. Bootstrapping PLS-SEM

Figure 2 presents the structural model generated from the bootstrapping analysis using SmartPLS. In this updated visualization, each latent variable SGI, EI, and ECI is displayed directly inside the elliptical nodes for improved clarity and alignment with formal SEM reporting standards. The arrows illustrate the hypothesized causal pathways among the constructs, while the numerical values positioned above each arrow represent the estimated path coefficients along with their statistical significance levels [37].

The results indicate that SGI exerts a significant positive effect on both EI (β = 0.491, p ¡ 0.001) and ECI (β = 0.435, p ¡ 0.001). Additionally, EI positively influences ECI (β = 0.491, p ¡ 0.001), confirming the mediating role of environmental improvements in driving economic outcomes. The R^2 values displayed below EI and ECI (0.801 and 0.752, respectively) further demonstrate the model's explanatory strength.

To validate these relationships, a full bootstrapping procedure was performed, and the statistical results including original sample values, mean values, standard deviations, t-statistics, and p-values are summarized in Table 1. These results provide strong empirical support for all proposed hypotheses and offer a comprehensive understanding of how smart grid integration contributes to environmental performance and economic benefits within the energy management ecosystem.

As presented in Table 1, the path coefficient analysis confirms that all hypothesized relationships in the model are positive and statistically significant. The updated structural model in Figure 2 shows the latent variables SGI , EI, and ECI embedded directly within the ellipses to provide clearer construct identification and alignment with formal SEM reporting standards.

Table 1. Path Coefficients and Significance Levels

Path	**Coefficient (O)**	**STDEV**	**T-Statistic**	**p-value**
Smart Grid Integration → Economic Impact	0.435	0.103	4.241	0.000
Smart Grid Integration → Environmental Impact	0.491	0.037	23.583	0.000
Economic Impact → Environmental Impact	0.491	0.116	4.233	0.000

The results indicate that SGI has a significant positive effect on ECI, with a path coefficient of 0.435, a t-statistic of 4.241, and a p-value of 0.000, supporting H1. Similarly, the relationship between SGI and EI is strongly significant, with a path coefficient of 0.491, an exceptionally high t-statistic of 23.583, and a p-value of 0.000, confirming H2. The findings highlight that greater adoption of smart grid technologies contributes directly to environmental improvements through enhanced energy efficiency and reduced emissions.

Additionally, EI demonstrates a meaningful positive effect on ECI, with a path coefficient of 0.491, a t-statistic of 4.233, and a p-value of 0.000, supporting H3. This relationship underscores the role of environmental performance as a driver of economic benefits, indicating that improvements in ecological outcomes can translate into enhanced cost savings, system optimization, and long-term economic resilience.

To further visualize the operational dynamics of smart grid adoption, this study provides an additional diagram that illustrates the integrated flow between technological components, environmental performance, and economic outcomes. As shown in Figure 3, the diagram highlights how smart grid technologies interact with renewable energy sources, control systems, and data analytics platforms to produce measurable environmental and economic benefits. This visual representation clarifies the systemic structure underlying the smart grid ecosystem and supports a more intuitive understanding of the interdependencies analyzed through the Structural Equation Modeling framework.

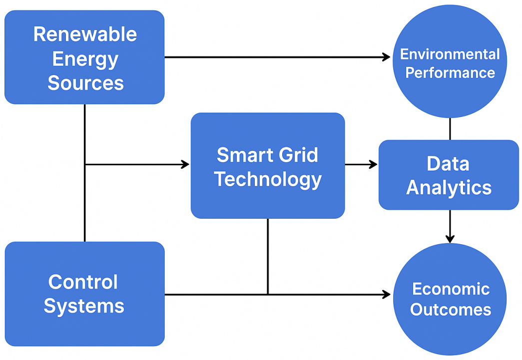

Figure 3. Conceptual flow model depicting how smart grid technologies influence environmental performance and economic efficiency

As illustrated in Figure 3, the smart grid ecosystem operates as a closed loop intelligent infrastructure where real-time monitoring, automated load balancing, and energy analytics converge to enhance overall system performance. This flow demonstrates how improved environmental conditions such as reduced emissions and optimized energy distribution translate into long term economic gains for both energy providers and consumers. The diagram reinforces the analytical findings of the study by showing that smart grid integration is not merely a technological upgrade, but rather a multidimensional system that advances sustainability and economic efficiency simultaneously.

In addition, the effect of Smart Grid Integration (SGI) on Economic Impact (ECI) is also positive and statistically significant, as shown by a path coefficient of 0.435, a t-statistic of 4.241, and a p-value of 0.000, thus supporting H2. This suggests that smart grid deployment contributes to improved economic outcomes by lowering operational costs and increasing the efficiency of energy distribution, which ultimately benefits both energy providers and consumers.

Furthermore, the relationship between Economic Impact (ECI) and Environmental Impact (EI) is likewise positive and significant, with a path coefficient of 0.491, a t-statistic of 4.233, and a p-value of 0.000, confirming H3. This finding indicates that improvements in economic performance are closely linked to enhanced environmental outcomes, demonstrating that cost-efficient energy systems simultaneously support sustainability goals. Collectively, these results highlight that smart grid integration drives environmental and economic advancements in parallel, strengthening its role as a critical enabler in the transition toward more sustainable and efficient energy infrastructures.

4.1. Model Fit and R^2 Values

The R^2 values for Environmental Impact and Economic Impact are 0.801 and 0.752, respectively [40, 41]. These high values demonstrate that the model has substantial explanatory power, with smart grid integration explaining 80.1% of the variance in environmental outcomes and 75.2% of the variance in economic outcomes. The high R^2 values validate the model's ability to predict the impact of smart grid integration on both environmental and economic dimensions.

The results provide strong evidence that smart grid integration plays a critical role in advancing both environmental and economic objectives. Each hypothesized relationship (H1, H2, and H3) was supported by statistically significant path coefficients, high T-values, and P-values below the 0.05 significance threshold. The findings suggest that smart grid technology is not only effective in reducing greenhouse gas emissions and improving energy efficiency but also offers substantial economic benefits by lowering costs and increasing financial savings. Moreover [42, 43], the indirect effect of environmental improvements on economic outcomes reinforces the value of sustainability as a pathway to economic advantage.

These results validate the dual benefits of smart grid integration, providing compelling evidence for the technology's contribution to both environmental sustainability and economic efficiency. These findings underscore the importance of investing in smart grid systems as a means to achieve holistic energy management that aligns with global sustainability goals and economic viability.

5. MANAGERIAL IMPLICATIONS

The findings of this study underline the importance for energy sector managers to prioritize strategic investments in smart grid infrastructure, as smart grid integration has been proven to reduce greenhouse gas emissions and improve energy efficiency. This not only aligns organizations with sustainability regulations and environmental standards but also enhances their competitive advantage in meeting global climate commitments. Implementing smart grid technologies enables companies to optimize energy distribution, reduce waste, and improve system reliability, helping them respond effectively to increasing environmental demands and stakeholder expectations.

In addition to environmental gains, managers should recognize the significant economic advantages associated with smart grid adoption. Smart grid systems can reduce operational costs, enhance financial performance, and generate long-term savings for both providers and consumers. Moreover, environmental improvements achieved through smart grids can yield indirect financial benefits, such as incentives, tax reductions, and enhanced corporate reputation. By integrating sustainability objectives with financial planning, managers can position their organizations as leaders in sustainable energy innovation while ensuring that environmental responsibility contributes positively to organizational growth and profitability.

6. CONCLUSION

The results of this study highlight the significant role of Smart Grid Integration (SGI) in promoting both environmental sustainability and economic efficiency. The strong positive relationship between SGI and environmental impact indicates that smart grid technology is effective in reducing greenhouse gas emissions and improving overall energy efficiency. Additionally, SGI contributes to economic advantages, as demonstrated by the substantial reduction in operational costs and increased cost savings for energy providers and consumers. These findings confirm that the integration of smart grids presents a dual benefit, simultaneously supporting ecological preservation and financial performance.

The novelty of this research lies in examining not only the direct effects of smart grid integration but also the indirect relationship between environmental performance and economic outcomes. The study reveals that environmental improvements driven by the implementation of smart grids can indirectly yield economic benefits through mechanisms such as regulatory incentives, improved corporate reputation, and enhanced consumer trust. This integrated perspective offers a more comprehensive understanding of sustainability, demonstrating that environmental responsibility and economic viability are not mutually exclusive, but rather interdependent in shaping energy sector transformation.

Future research is recommended to explore the application of smart grid integration across different regional and industrial contexts, as variations in regulatory frameworks, energy infrastructure readiness, and technological adoption rates may influence the effectiveness of SGI. Further studies could also incorporate real-time energy consumption data, consumer behavioral responses, and life cycle environmental assessments to deepen the empirical insights. Expanding the scope of research to include renewable energy microgrids, digital twin models, and advanced demand response systems could provide valuable contributions to the development of smarter, more sustainable, and economically resilient energy systems in the future.

7. DECLARATIONS

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7.2. Author Contributions

Conceptualization: RE; Methodology: FP; Software: RE; Validation: MA and LN; Formal Analysis: MS and LN; Investigation: FP; Resources: RE; Data Curation: LN; Writing Original Draft Preparation: FP and Ms; Writing Review and Editing: MA and RE; Visualization: RE and MS; All authors, RE, FP, MA, LN, and MS have read and agreed to the published version of the manuscript.

7.3. Data Availability Statement

All data supporting the findings of this study are available from the corresponding author upon the submission of a justified request.

7.4. Funding

No external funding, grants, or institutional financial contributions were provided for the conduct of this research or the preparation of this manuscript.

7.5. Declaration of Conflicting Interest

The authors state that they have no known financial, personal, or professional conflicts of interest that could have influenced the execution, analysis, or reporting of this work.

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