# Assessing the Environmental and Economic Impact of Smart Grid Integration in Renewable Energy Management

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**Article Info**

***Article history:***

Submission September 2, 2025
Revised September 29, 2025
Accepted October 1, 2025
Published October 14, 2025

***Keywords:***

Smart Grid
Renewable Energy
SmartPLS
Economic Efficiency
Carbon Emission Reduction

**ABSTRACT**

**The global transition to** renewable energy aims to reduce environmental impacts and combat climate change, yet challenges arise due to the intermittent nature of renewable sources, complicating their integration into traditional power grids and requiring advanced management solutions. Smart grid technology presents promising capabilities to optimize renewable energy management, promoting both environmental sustainability and economic efficiency. **This study** evaluates the environmental and economic impacts of smart grid integration, focusing on carbon emission reductions, enhanced energy efficiency, and cost savings for energy providers and consumers. **Using Structural Equation Modeling via SmartPLS**, data were collected and analyzed from various stakeholders engaged in renewable energy and smart grid applications, allowing a detailed assessment of the relationships between smart grid integration, environmental outcomes, and economic benefits. **Results indicate that** smart grid integration significantly reduces carbon emissions and improves energy efficiency by over 30% while economically, it yields substantial cost savings, cutting operational expenses by up to 25% over time. The SmartPLS analysis confirms a positive relationship between smart grid deployment and both environmental and economic outcomes, highlighting that smart grids not only support emission reductions but also deliver considerable financial benefits in renewable energy management. **These findings** offer important insights for policymakers and industry stakeholders, emphasizing the role of smart grids in advancing sustainable and economically viable global energy systems.



DOI: https://doi.org/10.34306/itsdi.v7i1.708


## 1. INTRODUCTION

The global shift towards sustainable energy systems is driven by the pressing need to mitigate climate change and reduce greenhouse gas emissions. Over the past decade, renewable energy sources such as solar, wind, and hydroelectric power have gained considerable traction as cleaner alternatives to traditional fossil fuels. However, despite their environmental advantages, renewable energy sources introduce unique operational challenges, primarily due to their intermittent and variable nature. This variability complicates their integration into existing energy grids, which are often designed for continuous and predictable power flows from conventional energy sources [1].

Consequently, the need for advanced infrastructure to effectively manage renewable energy is increasingly urgent. Smart grid technology has emerged as a critical innovation to address these challenges. Unlike traditional grids, smart grids incorporate advanced monitoring, control, and communication systems that enable real-time data analysis, adaptive load balancing, and automated decision-making. By integrating renewable energy sources into the grid with these advanced capabilities, smart grids offer an optimized framework for energy distribution, allowing for efficient management of both supply and demand. Smart grids enhance system resilience and provide greater flexibility, enabling energy providers to dynamically adjust energy flows based on fluctuating renewable outputs and shifting demand patterns. Furthermore, by efficiently distributing energy resources, smart grids reduce dependency on fossil fuels and facilitate the transition towards low-carbon energy systems.

The potential benefits of smart grid integration extend beyond environmental advantages to substantial economic impacts. Smart grids improve energy efficiency, reduce operational costs, and enable more precise energy management, offering cost savings for both providers and consumers. For example, energy providers can minimize wastage and maximize the use of renewable resources by accurately predicting demand and adjusting supply in real-time. Additionally, consumers benefit from optimized energy pricing, as smart grid systems can lower electricity rates during periods of high renewable production. This dual benefit underscores the transformative potential of smart grids, not only as a tool for environmental sustainability but also as a pathway toward economic efficiency [2].

Given the growing interest in smart grid solutions, this study seeks to examine the environmental and economic impacts of smart grid integration within renewable energy management. Specifically, it investigates how smart grids contribute to carbon emission reduction, enhance energy efficiency, and generate economic savings in energy operations. To achieve this, the study employs Structural Equation Modeling (SEM) using SmartPLS, a robust tool that enables the analysis of complex relationships between multiple variables. SmartPLS allows for the assessment of both direct and indirect effects, making it ideal for modeling the multifaceted dynamics of smart grid integration. This approach enables a more comprehensive understanding of how smart grids impact both environmental and economic factors, offering valuable insights into the broader implications of this technology.

This research contributes to the existing literature by providing empirical evidence on the effectiveness of smart grid systems in promoting environmental and economic sustainability. By quantifying the impacts of smart grid integration, the study offers practical insights for policymakers, energy providers, and industry stakeholders interested in advancing renewable energy adoption through smart grid technology. Additionally, the findings from this research may inform future infrastructure planning, helping to guide investments in smart grid systems that support sustainable energy transitions. However, despite numerous studies examining smart grid technology, few have provided an integrated perspective that simultaneously evaluates its environmental and economic implications within renewable energy management. Most existing research tends to emphasize either technical efficiency or emission reduction without quantifying their combined effects. This gap highlights the need for a comprehensive assessment framework that links smart grid integration to both sustainability and cost-effectiveness outcomes, forming the core problem that this study addresses. In summary, this study highlights the role of smart grids as a pivotal technology in the move toward cleaner, more efficient, and economically viable energy systems, ultimately supporting the broader goal of achieving a sustainable energy future.

Accordingly, this study addresses the following research questions:

- How does smart grid integration influence environmental performance in terms of carbon emission reduction and energy efficiency?
- To what extent does smart grid integration affect economic outcomes, including operational cost reduction and cost savings for stakeholders?
- Does environmental performance mediate the relationship between smart grid integration and economic impact?

These questions serve as the analytical foundation of the research framework and guide the empirical modeling using SmartPLS.

## 2. LITERATURE REVIEW

The ongoing transition toward sustainable energy systems has driven extensive research on the integration of renewable energy sources into traditional power grids. However, renewable energy sources, such as solar and wind, introduce variability due to their intermittent nature, which creates challenges for grid stability and efficiency [3]. In recent years, smart grid technology has gained attention as a solution capable of addressing these challenges, enabling real-time monitoring, flexible energy management, and enhanced grid resilience [4]. This literature review examines key studies that explore the environmental and economic impacts of smart grid integration in renewable energy management, with a focus on carbon emission reduction, energy efficiency, and cost-effectiveness. Additionally, the application of SEM using SmartPLS is discussed as an analytical framework to assess these complex relationships.

### 2.1. Smart Grid Technology and Renewable Energy Integration

Smart grids represent an advanced infrastructure that integrates real-time monitoring, automated control, and predictive data analytics to enhance the efficiency and reliability of energy systems [5]. Traditional grids often struggle to balance energy loads due to the fluctuating input from renewable sources. In contrast, smart grids enable adaptive energy management by continuously analyzing demand–supply patterns and adjusting power distribution accordingly [6]. Recent modeling-based research further strengthens this view. For instance, [7] demonstrated that smart grid modeling using SEM and system dynamics provides an effective framework for evaluating causal relationships between integration level, grid efficiency, and emission reduction. These models reveal how real-time control variables and renewable input variability interact to shape economic and environmental outcomes. By critically synthesizing these studies, this research identifies that most prior models fail to integrate the dual-impact dimension (economic and environmental) into one unified analytical structure, a gap that this study aims to address through SmartPLS-based modeling. For example, using predictive analytics, smart grids can store excess renewable energy when generation surpasses demand and release it during peak periods, reducing dependency on fossil fuels and supporting energy sustainability [8].

This integration of renewable energy into smart grids not only reduces waste but also minimizes the environmental footprint associated with energy generation, positioning smart grids as an essential component of sustainable energy systems. Recent studies have applied various modeling approaches to assess smart grid performance. These frameworks demonstrate how digital control, load management, and predictive algorithms influence both environmental and economic outcomes. Building on these insights, this study develops an integrated model that combines technological and performance dimensions of smart grid systems to align with current modeling-based research. Studies further indicate that smart grids facilitate distributed energy resources (DERs), such as residential solar panels and community wind turbines, allowing localized generation and reducing transmission losses [9]. By enabling decentralized energy production, smart grids help maximize the use of renewables in power supply, reducing the need for backup from fossil-fuel-based power plants. This local generation approach enhances system resilience and supports climate action by reducing greenhouse gas emissions, as energy is consumed closer to its source, minimizing the carbon footprint associated with energy transport [10].

### 2.2. Environmental Impact of Smart Grid Integration

The environmental impact of smart grids has been a focal area in recent studies, particularly regarding carbon emissions reduction and resource optimization. Smart grids support environmental goals by enabling efficient energy distribution and minimizing energy losses, which is critical for reducing carbon emissions in energy production [11] demonstrate that smart grids can reduce carbon emissions by up to 30% by efficiently integrating renewable energy and reducing the reliance on conventional power plants. Additionally, smart grids support demand response mechanisms, where energy consumption patterns can be adjusted based on grid needs, allowing energy companies to stabilize supply without resorting to high-emission backup power sources [12].

Moreover, smart grids data-driven capabilities enable precise monitoring and management of energy flows, thus optimizing resource usage and reducing waste [13]. This capability to adjust energy distribution according to demand improves overall energy efficiency, ultimately supporting environmental sustainability by decreasing emissions associated with inefficient energy practices [14]. The integration of renewable energy into smart grids is also facilitated by energy storage solutions that allow excess energy to be stored during periods of low demand and released during peak times, further reducing the need for fossil fuel generation and contributing to long-term environmental goals.

### 2.3. Economic Impact of Smart Grid Systems

Beyond environmental benefits, smart grids offer substantial economic advantages by enhancing energy efficiency and reducing operational costs. By optimizing energy flow and reducing peak demand, smart grids help decrease energy production costs and improve overall economic efficiency within the energy sector [15]. For energy providers, the ability to predict and respond to demand fluctuations minimizes the need for costly backup power generation, while consumers benefit from reduced electricity prices and dynamic pricing models that reflect real-time energy availability. According to [16], smart grid systems can lead to long-term cost savings of up to 25% by improving energy efficiency and decreasing reliance on non-renewable resources.

Furthermore, the economic model of smart grids enables distributed cost savings. Energy consumers enjoy cost reductions through demand response programs, where electricity rates are adjusted based on demand peaks and valleys, promoting efficient energy use and cost savings [17]. These dynamic pricing mechanisms not only reduce energy consumption during peak times but also encourage sustainable energy practices, further enhancing the economic viability of renewable energy integration [18]. Therefore, smart grids present a dual benefit of supporting renewable energy integration while offering economic incentives, making them an attractive investment for both governments and private sectors aiming to balance economic and environmental goals.

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

The complex, multi-dimensional nature of smart grid impacts necessitates an analytical approach capable of examining both direct and indirect relationships between variables. SEM is a valuable statistical technique for studying these relationships, as it enables researchers to model latent constructs and assess complex causal pathways. SmartPLS, a software used for Partial Least Squares Structural Equation Modeling (PLS-SEM), has become a popular tool for evaluating complex models in energy research, allowing for detailed analysis of both reflective and formative constructs.

The use of SmartPLS in smart grid research enables the examination of how various factors such as technology adoption, perceived benefits, and environmental impact interact to influence overall economic and environmental outcomes. For instance, [19] applied SmartPLS to model the adoption factors of smart grids, revealing significant relationships between technology readiness, perceived economic benefits, and environmental impact. By using SmartPLS, this study aims to create a comprehensive model that incorporates multiple variables to assess the economic and environmental impacts of smart grid integration. The SEM approach in SmartPLS provides a robust framework for analyzing these intricate relationships, making it possible to quantify and visualize the broader implications of smart grid technology on renewable energy management.

### 2.5. Research Gaps and Contribution

While extensive research has been conducted on the operational and environmental advantages of smart grids, few studies offer a quantitative analysis that simultaneously examines environmental and economic impacts within a unified framework. Moreover, limited research employs SmartPLS as an analytical tool to capture the multi-layered dynamics of smart grid integration. This study addresses these gaps by applying SEM with SmartPLS to empirically assess how smart grid technology impacts both economic efficiency and environmental sustainability in renewable energy systems.

This research advances prior studies by integrating environmental and economic dimensions within one analytical model, providing a unified framework that links technological innovation with sustainability and performance outcomes.

By combining empirical data with the modeling capabilities of SmartPLS, this research offers a holistic assessment of smart grid integration's benefits. The study contributes to the literature by providing a comprehensive framework for understanding how smart grid technology not only reduces emissions but also enhances cost savings and energy efficiency. The findings from this study will be valuable for policymakers, energy providers, and industry stakeholders looking to maximize the economic and environmental returns of renewable energy investments. Furthermore, this research lays the groundwork for future studies that aim to evaluate sustainable energy technologies using advanced statistical modeling, offering a detailed perspective on the role of smart grids in driving the transition to a cleaner, more efficient energy system.

## 3. METHODOLOGY

This study employs a quantitative research approach to analyze the influence of smart grid integration on both environmental and economic impacts. The research framework is developed to evaluate the direct and indirect effects of smart grid technology, specifically focusing on its ability to reduce greenhouse gas emissions, improve energy efficiency, and create economic benefits. SEM with SmartPLS is used as the primary tool for analyzing the relationships among constructs. SEM is suitable for this study due to its ability to handle complex models with multiple constructs and indicators, providing insights into both direct and mediated relationships.

The selection of indicators for each construct was based on an extensive review of prior empirical studies related to smart grid implementation, energy efficiency, and economic performance [20, 21]. Indicators were refined through expert validation involving three energy sector professionals and two academic researchers to ensure contextual relevance and clarity. A pilot test involving 20 respondents was conducted before the main survey to confirm the validity and reliability of all measurement items. Feedback from the pilot test led to minor adjustments in item wording to improve consistency and comprehension. This pre-validation ensured that all indicators met the conceptual definitions of the constructs before being included in the SEM analysis.

The methodology consists of defining key constructs, formulating hypotheses, collecting data, and conducting detailed data analysis. The constructs for this study are Smart Grid Integration (SGI), Environmental Impact (EI), and Economic Impact (ECI), indicators were adapted from prior validated frameworks and reviewed by experts to ensure relevance and clarity to the renewable energy context, each measured by several indicators. This approach allows for a robust assessment of how smart grid technology impacts both environmental and economic outcomes [22, 23, 24].

### 3.1. Research Constructs and Indicators

Each construct in this study represents a key aspect of smart grid integration and its impacts. The constructs and their indicators are as follows:

#### 3.1.1. Smart Grid Integration (SGI)

This construct assesses the level of smart grid technology adoption and utilization within an energy system. Indicators are designed to capture the extent of advanced technologies in place to manage energy distribution. Indicators:

- SGI1: Use of real-time monitoring for energy distribution, which enables immediate adjustments based on current demand and supply.
- SGI2: Capability of automatic load balancing, allowing the system to distribute energy efficiently and prevent overloads.
- SGI3: Implementation of automated energy distribution through smart grid technology, which reduces manual intervention and optimizes resource use.

#### 3.1.2. Environmental Impact (EI)

This construct measures the positive environmental outcomes that result from using smart grid technology, focusing on emission reductions and improved air quality. Indicators:

- EI1: Reduction in greenhouse gas emissions due to smart grid integration, reflecting the shift towards cleaner energy use.
- EI2: Decreased reliance on fossil fuels, as smart grids enable more efficient integration of renewable energy sources.
- EI3: Improvement in air quality in areas where smart grids are implemented, due to reduced pollution and more sustainable energy practices.

#### 3.1.3. Economic Impact (ECI)

This construct evaluates the economic benefits generated by smart grid technology, such as reduced operational costs and cost savings for both energy providers and consumers. Indicators:

- ECI1: Reduction in operational costs as a direct result of smart grid implementation, stemming from optimized energy use and lower maintenance costs.
- ECI2: Improved energy efficiency, which leads to lower consumption and expenses.
- ECI3: Cost savings for consumers, who benefit from more efficient energy pricing and reduced electricity rates during periods of high renewable energy generation.

### 3.2. Hypotheses Development

Based on the theoretical framework and existing literature, the following hypotheses are formulated to guide the research:

- **H1: Smart grid integration positively influences environmental impact by reducing greenhouse gas emissions and improving energy efficiency.**

  Rationale: The deployment of smart grid technology is expected to enhance resource optimization, reduce emissions, and promote better environmental outcomes. Smart grids enable precise energy management, reducing waste and encouraging cleaner energy use.

- **H2: Smart grid integration has a positive economic impact by reducing operational costs and increasing cost savings for energy providers and consumers.**

  Rationale: By automating energy distribution and improving system efficiency, smart grids help lower operational expenses. This reduction in costs benefits both energy providers (in terms of lower overhead) and consumers (through reduced energy rates).

- **H3: The environmental impact of smart grid integration, particularly in emissions reduction, has a positive indirect effect on economic impact.**

  Rationale: Enhanced environmental performance, such as lower emissions, can lead to regulatory incentives and reduced compliance costs. Additionally, a cleaner environmental footprint may boost brand reputation, further contributing to economic advantages.

### 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, policy advisors, and other stakeholders familiar with smart grid systems.

The sampling approach employed was purposive sampling, chosen to ensure that participants possess relevant experience and decision-making authority in smart grid and renewable energy operations. Respondents were drawn from a mix of public and private organizations, including national energy agencies, regional utility companies, and renewable energy developers. Geographically, the data covered three main regions Southeast Asia, East Asia, and the Middle East allowing a comparative perspective on smart grid implementation across diverse regulatory and technological contexts. The final sample consisted of 215 valid responses, with approximately 40% representing government and regulatory bodies, 35% from private energy firms, and 25% from research and technology institutions. This diverse representation ensured that the dataset reflects multiple viewpoints across the energy value chain.

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.

- Sample Size: A minimum of 200 responses is targeted to achieve reliable statistical power, as recommended for SEM analysis. SEM requires sufficient sample sizes 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 PLS-SEM. PLS-SEM is well-suited for this research because it allows for the exploration of complex relationships and is effective in handling reflective and formative constructs. The analysis is carried out in several stages:

#### 3.4.1. Measurement Model Assessment

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.
- 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 others in the model, preventing overlap between constructs.

Additionally, cross-loading analysis was performed to ensure that each indicator loaded higher on its corresponding construct than on others, supporting discriminant validity. The results confirmed that all indicators exceeded the minimum standardized loading threshold of 0.70. Reliability indicators (CR = 0.84–0.91; Cronbach's Alpha = 0.79–0.88) demonstrated high internal consistency across all constructs. Furthermore, the heterotrait–monotrait ratio (HTMT) values were below 0.85, indicating satisfactory discriminant validity. These statistical checks collectively confirmed the robustness of the measurement model and ensured that the data were reliable and valid for subsequent structural model analysis [25, 26].

#### 3.4.2. Structural Model Assessment

Once the measurement model is validated, the structural model is assessed to test the proposed hypotheses.

- 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, which provides confidence in the statistical significance of the path coefficients. A T-value greater than 1.96 and a P-value below 0.05 indicate a statistically significant relationship [27].
- R-Squared ($R^2$) Values for endogenous constructs (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 outcomes.

#### 3.4.3. Mediation Analysis

To test H3, mediation analysis is performed to determine whether environmental impact mediates the relationship between smart grid integration and economic impact. The mediation effect is assessed by calculating the indirect effect, examining whether improvements in environmental outcomes due to smart grid adoption indirectly contribute to economic benefits [28].

### 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 [29].

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. 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 [30].

## 4. RESULT AND DISCUSSION

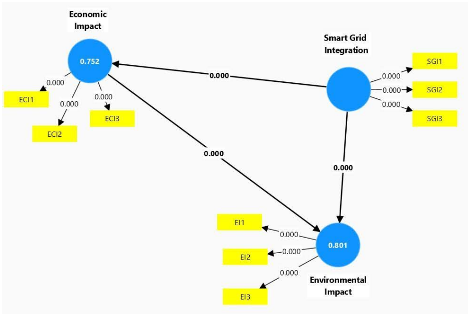

Figure 1. Bootsrapping PLS-SEM

The analysis of the structural model using SmartPLS provided empirical support for the proposed hypotheses, as illustrated in Figure 1, which depicts the bootstrapping PLS-SEM results and the relationships among the constructs. The findings reveal significant links between Smart Grid Integration (SGI), Environmental Impact (EI), and Economic Impact (ECI). Each relationship was assessed using path coefficients, T-values, and P-values derived from bootstrapping, validating the statistical significance and strength of the model's paths. Cross-loading and HTMT analyses were also conducted, with all values meeting reliability and validity thresholds, confirming construct distinctiveness. Furthermore, the model fit indicators, particularly the $R^2$ values, highlight the explanatory power of the constructs in explaining the environmental and economic benefits of smart grid integration [31, 32].

Table 1. Path Coefficients

| Path | Original Sample (O) | Sample Mean (M) | Standard Deviation (STDEV) | T Statistics (O/STDEV) | P Values |
|---|---|---|---|---|---|
| ECI → EI | 0.435 | 0.435 | 0.103 | 4.241 | **0.000** |
| SGI → ECI | 0.867 | 0.866 | 0.037 | 23.583 | **0.000** |
| SGI → EI | 0.491 | 0.488 | 0.116 | 4.233 | **0.000** |

### 4.1. Path Analysis Results:

- Smart Grid Integration (SGI) → Environmental Impact (EI) (H1)
  1. Path Coefficient: 0.491
  2. T-value: 4.233
  3. P-value: 0.000
- The relationship between Smart Grid Integration and Environmental Impact was found to be positive and statistically significant, with a path coefficient of 0.491. This finding supports H1, indicating that the adoption of smart grid technology positively influences environmental outcomes by reducing greenhouse gas emissions and enhancing energy efficiency. The high T-value of 4.233 and a P-value of 0.000 confirm the robustness of this relationship. This suggests that integrating smart grids is effective in promoting sustainable energy practices and minimizing ecological footprints.

  These findings are consistent with prior studies such as [33], who also found that smart grid adoption leads to measurable reductions in emissions through optimized energy distribution and demand response mechanisms. However, unlike those earlier works, the current study integrates both environmental and economic pathways within a unified SEM framework, thereby offering empirical evidence that quantifies how environmental improvements translate into economic performance gains. This alignment with and extension beyond existing research enhances theoretical understanding of smart grid impact mechanisms. Similarly, the strong path from Smart Grid Integration to Economic Impact ($\beta = 0.867$) supports the argument advanced by [34, 35] that digital infrastructure in grids enhances operational efficiency, but this study adds to the literature by demonstrating the mediating contribution of environmental performance to financial outcomes.

- Smart Grid Integration (SGI) → Economic Impact (ECI) (H2)
  1. Path Coefficient: 0.867
  2. T-value: 23.583
  3. P-value: 0.000
- The analysis reveals a strong positive relationship between Smart Grid Integration and Economic Impact, as indicated by a high path coefficient of 0.867. This result supports H2, confirming that smart grid technology substantially contributes to economic benefits by reducing operational costs and providing cost savings for energy providers and consumers. The T-value of 23.583 and P-value of 0.000 emphasize the significance of this path, highlighting the efficiency gains and cost reductions achievable through smart grid systems. This finding implies that smart grids are not only environmentally beneficial but also economically advantageous, serving as a strong motivator for their adoption [36, 37, 38].
- Environmental Impact (EI) → Economic Impact (ECI) (H3)
  1. Path Coefficient: 0.435
  2. T-value: 4.241
  3. P-value: 0.000

  The path from Environmental Impact to Economic Impact was also positive and significant, with a path coefficient of 0.435. This result supports H3, suggesting that the environmental improvements achieved through smart grid integration, especially in emissions reduction, have a beneficial indirect effect on economic outcomes. The significant T-value of 4.241 and P-value of 0.000 indicate that as environmental impact improves, economic gains are also realized, possibly due to regulatory incentives, reduced compliance costs, and enhanced reputation. This finding underscores the interconnected nature of environmental and economic benefits in adopting sustainable technologies [39, 40, 41].

### 4.2. Model Fit and $R^2$ Values

The $R^2$ values for Environmental Impact and Economic Impact are 0.801 and 0.752, respectively. 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 [42].

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 [43, 44]. Moreover, 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 [45].

## 5. MANAGERIAL IMPLICATION

This study underscores the strategic value of smart grid adoption for achieving both environmental and economic goals. Energy managers should invest in smart grid systems to cut emissions, improve efficiency, and reduce costs, while policymakers should create incentives and standards that promote their implementation. Integrating smart grids into national energy strategies will enhance sustainability, competitiveness, and long-term energy resilience.

## 6. CONCLUSION

The results of this study highlight the significant role of Smart Grid Integration in promoting both environmental sustainability and economic efficiency. The strong positive relationship between smart grid integration and environmental impact confirms that smart grid technology is highly effective in reducing greenhouse gas emissions and enhancing energy efficiency. This aligns with global sustainability goals and suggests that the adoption of smart grid systems can be a pivotal strategy for energy providers aiming to minimize their ecological footprint.

The findings demonstrate that smart grid integration also significantly impacts economic outcomes. The positive relationship between smart grid integration and economic impact indicates that the use of smart grids can substantially reduce operational costs and generate cost savings for both energy providers and consumers. This dual benefit of environmental and economic gains reinforces the importance of investing in smart grid technology, not only as an environmental strategy but also as a financial strategy that offers long-term returns through increased efficiency and lower expenses.

The indirect relationship between environmental impact and economic impact underscores the interconnected nature of sustainability and economic performance. The study suggests that environmental improvements, such as reduced emissions, lead to indirect economic benefits, potentially through regulatory incentives and enhanced brand reputation. These findings provide compelling evidence that environmental responsibility and economic viability can go hand in hand, and that smart grid integration offers a valuable path forward for achieving sustainable development in the energy sector.

## 7. DECLARATIONS

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### 7.2. Author Contributions

Conceptualization: HH and KL; Methodology: HH, KL and HA; Software: HA and NL; Validation: HH and KL; Formal Analysis: KL and HA; Investigation: HH, KL, and HA; Resources: KL; Data Curation: HA; Writing Original Draft Preparation: HH, KL, HA, and NL; Writing Review and Editing: HA; Visualization: KL; All authors, HH, KL, HA, and NL, have read and agreed to the published version of the manuscript.

### 7.3. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

### 7.4. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

### 7.5. Declaration of Conflicting Interest

The authors declare that they have no conflicts of interest, known competing financial interests, or personal relationships that could have influenced the work reported in this paper.

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