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Full Length Article

Research on low-carbon development path of new energy industry under the background of smart grid

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A R T I C L E I N F O

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A B S T R A C T

Objectives: The transition to a low-carbon and sustainable energy system is essential to combating climate change and ensuring the long-term viability of the global energy industry. Smart grid technologies are emerging as a transformative force in this transition. This research explores the multifaceted impact of smart grid technologies on the new energy industry and evaluates the influence of policies and regulations in shaping its development.
Methods: The study employs a mixed-method approach, combining quantitative analysis of key performance indicators (KPIs) and a qualitative examination of stakeholder perspectives. The quantitative analysis focuses on the impact of smart grids on renewable energy penetration, carbon emissions, and energy efficiency. The qualitative analysis draws on interviews with experts from industry, academia, and government to gain insights into the role of policies and regulations in driving smart grid development.
Results: The quantitative analysis reveals a significant increase in renewable energy penetration, a reduction in carbon emissions, and enhanced energy efficiency in regions with high smart grid adoption. These findings indicate the substantial impact of smart grid technologies in facilitating the transition to a clean and sustainable energy system. The qualitative analysis highlights the role of policies and regulations in driving the growth of renewable energy capacity, reducing carbon emissions, and creating jobs in the new energy industry. Supportive regulatory frameworks have been instrumental in stimulating investment in smart grid technologies and renewable energy projects. A regression analysis was conducted to shed light on the impact of sustainability indicators, economic assessments, and renewable energy capacity on carbon emissions. The analysis shows that these variables significantly influence carbon emissions, providing insights for policymakers and industry stakeholders.
Conclusion: The findings of this study underscore the importance of smart grid technologies and supportive regulatory frameworks in facilitating sustainable energy development. Smart grid technologies play a critical role in enabling the integration of renewable energy into the grid, improving energy efficiency, and reducing carbon emissions. Governments and industry stakeholders should collaborate to accelerate the deployment of smart grid technologies and create a supportive policy environment for the new energy industry.Research and development should be funded for innovative smart grid technology.

1. Introduction

The smart grid is based on a coordinated, rapid, bidirectional correspondence organization and uses state of the art gear, control, and choice emotionally supportive network advancements to be reliable, protected, reasonable, effective, and harmless to the ecosystem. Self-mending, rousing and including clients, frustrating attacks, providing power quality that fulfills 21st century client requests, empowering admittance to a scope of force creation structures, initiating power showcases, and enhancing resource applications for viable activity are a portion of its key attributes. Its application degree is becoming perpetually expansive. For example, a few locales have as of late fabricated new smart urban communities by combining smart grids with wise transportation (Ringenson et al., 2017). It has gotten far reaching consideration from one side of the planet to the other as a pivotal part of the energy web and is currently a recent fad in the extension of the worldwide power grid (Thompson, 2023).

The various elements that affect smart grid development in different nations change the focus of smart grid development. Fig. 1 and Table S1 displays the top ten nations where the federal government invested in

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smart grids in 2010. Their enterprise has grown to $18.4 billion and will grow. Europe's main priorities are data innovation, exchange expansion, and force grid framework development (Norouzi et al., 2023). The US prioritises energy efficiency and low-carbon development. The green economy emphasises employment in Japan. China needs to improve its electricity grid's asset portion, welfare, and functionality. China develops smart grids in three stages: planned pilot, full development, and guiding and further developing. Smart grid assumption at each level is shown in Fig. 2 and Table S2.

Recent high-speed development has normalised smart grid expansion internationally. Since industrialised nations like Europe and the US are experts in electrical grid construction, building, and operation, smart grid evaluation has been extensively studied. Experience and major achievements have been achieved (Ni, et. al, 2010). China's smart grid expansion has also reached a critical stage. By speeding development and construction, provincial electrical grid enterprises have met the State Grid Corporation's smart network strategy. To evaluate the smart grid's progress and identify the optimum path for its expansion, a credible evaluation system and methodology are needed. In light of the aforementioned, this study constructs an index system that combines the effect layer and the base layer, measures smart grid growth in a given region, finds its weaknesses, and gives optimisation recommendations.

1.1. Attaining a low-carbon power system model goal

Modern life demands power, and customers want security and reliability. Power supply reliability should be maintained during the low-carbon power framework transition. Cost (peripheral benefit of creating limit) in spare limit and extra limit of the worth arrangement of supply dependability (accessible power misfortune to assess) a compromise between to achieve an elevated degree of influence framework unwavering quality, the need to decide the ideal savings limit of a framework that balances supply unwavering quality and power cost Each nation's value is calculated differently (Gore et al., 2023). The UK energy market manual excludes clients who voluntarily lower power requests because force supply clients' consistency is uncertain. Find the smallest value of the producing limit between EEU that an optimal extra limit issues for a power framework with low dependability, where any minor shift over time will provide the framework a vital benefit. Increasing the saving limit will temporarily boost energy prices due to the power supply system's consistency (Musah, 2023; Zhang et al., 2023). China shouldn't judge the framework by its inability to assess electricity reliability. As the energy age changes, so will esteem and the EEU unimportant limit. Future domestic renewable and clean energy age limit is extending to achieve non-fossil energy objective. It's not scientific to evaluate renewable energy age restrictions like breeze ranches (Fischer et al., 2018). Experts should examine a low-carbon home electrical system to guarantee supply dependability. The most essential low-carbon power framework throughout the low-carbon economic transition must fulfil several requirements, including:

(1) Sufficient, growing limitations on low-carbon generator power age and supply and
(2) Solid fuel sources to assure power generation at all times.

In its "UK Low Carbon Progress Plan," the English government highlights the necessity of a low-carbon economy for 21st-century financial prosperity. The US federal government and several state legislatures have also embraced "renewable energy grid runs the show" requiring power suppliers to accept Kyrgyzstan's clean and Web energy age limitations to limit fossil energy production.China is accelerating the construction of its "Twelfth Long-term Plan," which prioritises energy planning, renewable energy, smart grid planning, Kyrgyzstan's growth, and grid planning to minimise carbon emissions (Nastasi & Lo Basso, 2017). We think market influences should restructure the electrical sector to decrease carbon emissions. If the market framework is missing, the public sector should play a vital role through carbon estimating policies that support specialist progress: supply energy generating and electrical firms data to make educated judgements and ensure energy security supplies; safeguarding vulnerable groups and developing markets, etc. In wealthy or emerging nations, only the government will support low-carbon energy (Rweyendela et al., 2023; Cowell and De Laurentis, 2022; Badami and Fambri, 2019). The public authority will support this important power structure change. Limiting public sector funding for low-carbon innovations like atomic power, CCS, and renewable energy.

1.2. Smart grid

To create a smarter, more dependable power system, the foundation and electrical energy framework need be updated. Smart grids provide advantages over traditional grids. Smart grids increase financial and

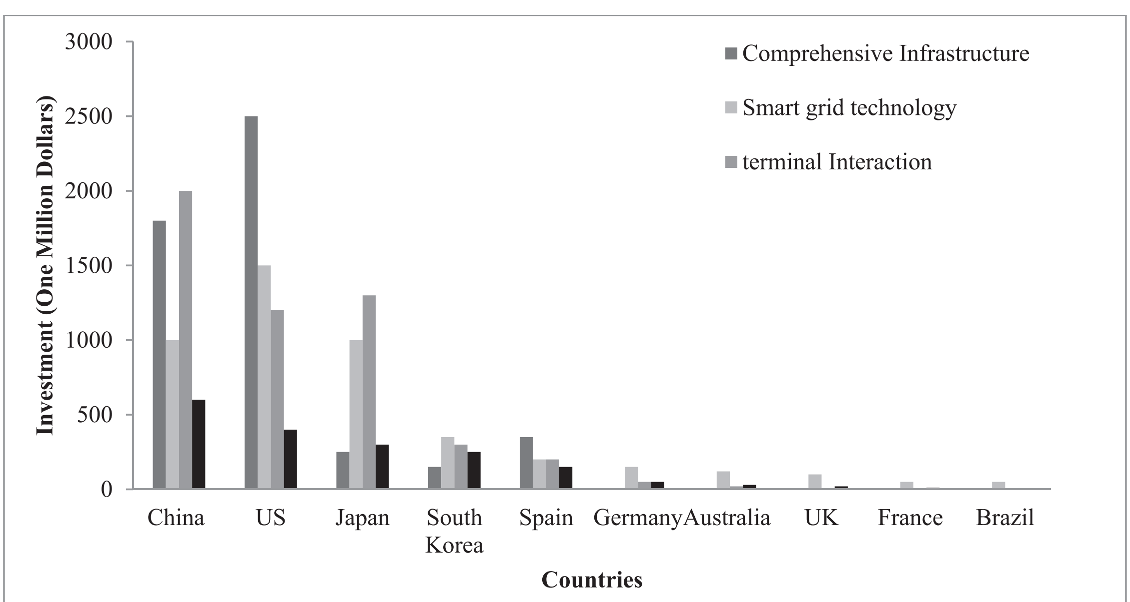


Fig. 1. Smart Grid Investment in the World's Leading Ten Nations.

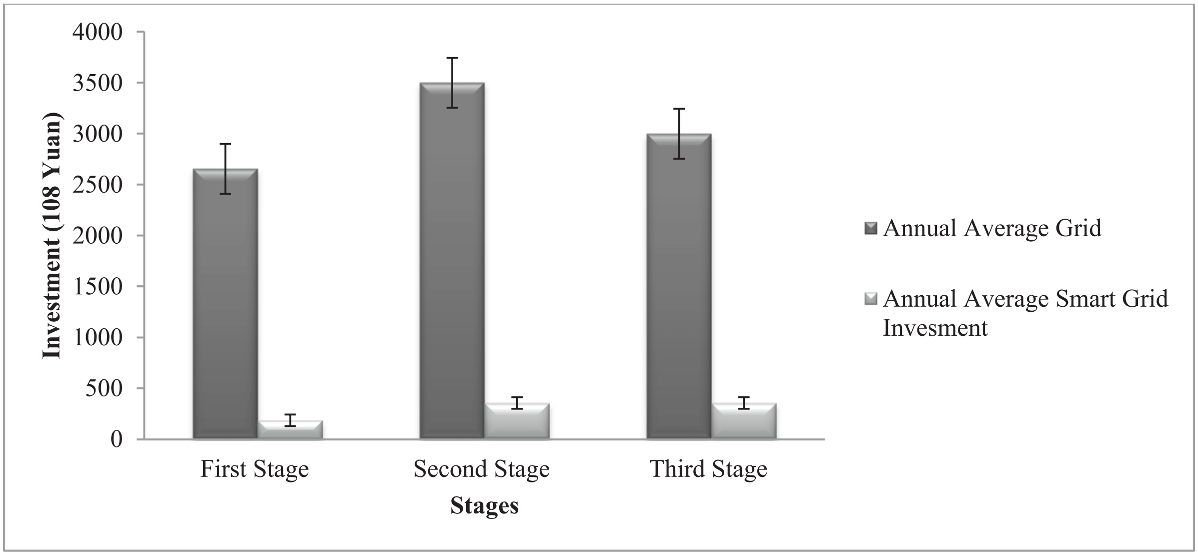


Fig. 2. Investment Progress in China across Various Stages.

operational grid sustainability and consistency (Duic et al., 2017). (Ikäheimo et al., 2018) depicts the smart grid more realistically. The US Branch of Energy's cutting-edge innovation-based grid drive is guaranteed by an insightful self-reaction or a smart grid that coordinates and consolidates advanced detecting, observing, control, and two-way interchanges into the flow power grid. Fig. 3 shows the smart grid essential chart. Sending the smart grid framework advances requests and increases energy security.

The smart grid handles uncommon events. The smart grid's three security goals are client explicit power supply accessibility, two-way communication, and client information security (Tuunanen et al., 2016). Smart grid management requires understanding the transmission system to improve system dependability. Despite energy efficiency issues along the dispersion line, this technique has certain economic benefits. Smart grid innovations like flexible AC transmission systems may let system administrators precisely monitor and manage grid energy flows. First, a modern sensor called a phasor estimate unit tracks specialised organisations' continual reaction, improving the power framework's efficiency (European Network of Transmission System Operators for Electricity, 2020). Second, smart grid mechanisation will function more autonomously, and distributed substation control will be improved.

1.3. *Enabling low-carbon path formation through smart grid power systems*

The smart grid's main goal is energy conservation. It then helps construct low-carbon electricity frameworks. Smart grid energy savings are prioritised immediately and backward. Expanded energy productivity alludes to end-use energy effectiveness, which decreases process misfortunes caused by power reserve funds, thereby reducing the size of the energy utilisation wellspring (Hurskainen, 2017). The basic house smart grid development organising papers state that every family energy production, transmission, and dissemination organisation can support low-carbon power. Ten smart grid innovations are being implemented: high-level transmission, dispersed age and miniature grid, energy-saving and high-buck voltage control, wind power, sun-based power age and organisation, the force of data criticism framework, energy proficiency and request reaction, and smart Engineering Celebration electrical analytic measure (Muller-Syring et al., 2017).

Massive wind power innovation, massive sun-oriented power age, and organisation innovation development underpin clean energy. Smart

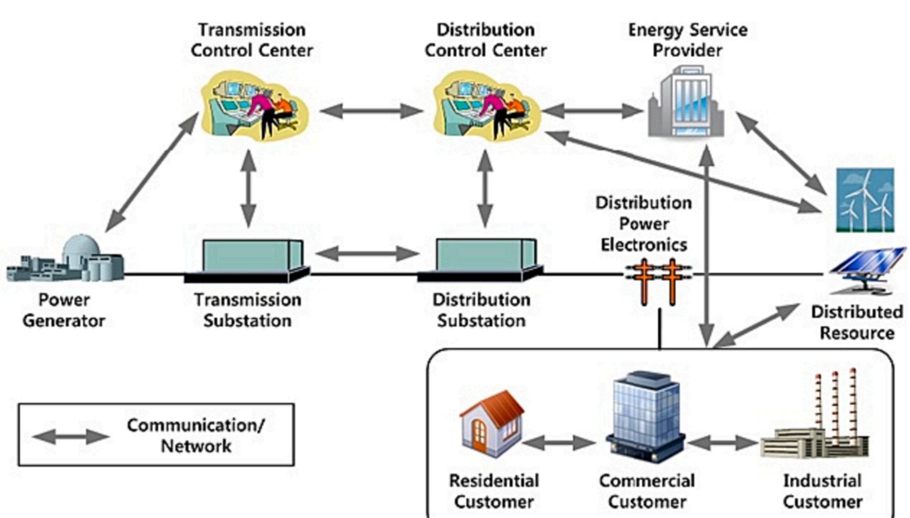


Fig. 3. Block outline of the Smart grid Concept.

grid innovation aims to improve the massive power grid's booking and dispatching framework, asset designation, complete gamble guard, logical direction, adaptable and effective innovation foundation, and fair market-accommodating sending (Battaglini et al., 2012; Amjith and Bavanish, 2022; Nowroozipour et al., 2023; Han et al., 2023; Lin et al., 2023; Chen et al., 2023). Smart booking technology, large-scale renewable energy that can be used in a power-age location, understanding the development of traditional fossil energy sources, and limiting carbon-based energy use from the power source (Ritola et al., 2014; Vandewalle et al., 2015; Simonis and Newborough, 2017). Conveyed age, tiny grid, and other multi-generational assets like clean energy developments reduce carbon-based energy usage.

Nyangaresi (2021) concluded that they offered a methodology for generating dynamic ephemeral and session keys. The security study demonstrates that it provides entity anonymity, mutual authentication, forward key secrecy, and untraceability. Furthermore, it has shown resilience against common smart grid vulnerabilities, including offline password guessing, denial of service (DoS), packet replays, privileged insider threats, man-in-the-middle (MitM) attacks, impersonation, and physical capture. Regarding performance, this protocol has the lowest execution times and bandwidth needs compared to other similar protocols. Nyangaresi et al., (2022b), Nyangaresi et al., (2022a) also determined that the system provides backward and forward key secrecy, anonymity, and is resistant to impersonation, session hijacking, privileged insider, side-channels, packet replays, packet injection, and privacy leakage attacks. He firmly holds the belief that, in terms of efficiency, a restricted number of elliptic curve multiplications and one-way hashing operations are performed during mutual authentication, message signing, and verification. This protocol demonstrates minimal computing and communication complexity when compared to its counterparts (Nyangaresi et al., 2022c; Nyangaresi, 2022d).

Research Objectives

- To investigate the impact of smart grid technologies on the new energy industry.
- To analyze the policies and regulations in place and how they affect the development of the new energy industry.
- To assess their potential to reduce carbon emissions and improve the overall sustainability of the energy system.

2. Literature review

Liwen et al. (2012) examined the relationship between smart grids and low-carbon financial concerns. They quantified the long-term impact of carbon emissions on the power sector and suggested the need for the development of low-carbon power solutions. Mechanical smart grid solutions for achieving low-carbon electricity were proposed. The direct smoothing method was found to increase power sector carbon emissions. The cost of carbon emissions was calculated using global carbon market estimates, revealing that the low-carbon advantage of smart grids amounted to 224.57 billion yuan, promising future development. Verbong et al. (2013) examined Dutch smart grid preliminary partner views and client collaboration practices. They utilized top-down meetings and smart grid project surveys. Their data indicated a clear trend towards giving customers more consideration in new smart grid projects. The study also highlighted the importance of prioritizing innovation and financial incentives while recognizing institutional issues. Creative ideas for exploring client commitment opportunities were deemed crucial. Pilot and exhibition projects that were either underway or planned provided an ideal context for such an analysis. The study emphasized the value of understanding smart grid social aspects and participating in global knowledge exchange to avoid fixation on a single approach.

Yan et al. (2015) examined request response dedication to increasing productivity and low-carbon energy-saving power frameworks. They analyzed a computerized request response framework and offered guidance for business, industrial, and residential customers. The study explored the interest response process, data exchange models, measurement, and verification approaches, as well as multi-stakeholder planning strategies. It also emphasized the completion of ADR business in smart grid UI standards to support demand-side management projects and maintain grid-client interoperability. Faerber et al. (2018) demonstrated how the value design of distribution organizations could adapt to a smart grid in a low-carbon economy. They used expert interview data to reconcile innovative pricing strategies and regulatory criteria. The study emphasized the need for political decisions on cost recovery and expenditure consolidation. Four key requirements were listed for the successful implementation of a new component, including the coordination of adjacent dispatch by Transmission System Operators (TSO) and Distribution Network Operators (DNO/DSO), the use of smart meters to monitor clients' grid use contributions, promotion of provider-DNO/DSO collaboration to provide power bill cost signals, and the establishment of a robust framework for sharing, billing, and transmitting information, potentially involving relaxation of existing privacy restrictions. The study suggested that future organizational assessment should focus on grid services and capabilities, rather than product power.

Deakin and Reid (2018) reviewed literature on smart urban communities and presented smart urban communities as potential web-based advancements from a Triple Helix perspective. The research offered a comprehensive integration of the material, highlighting the role of smart urban communities in the Internet of Things (IoT), digital systems, data management, renewable energy, and cloud computing. The study focused on regional IoT development catering to urban infill, mass retrofits, and expansions, which are essential for smart urban communities. While the study primarily evaluated mass retrofit plans, it also demonstrated how the metropolitan design of such local advancements mattered. It highlighted that the significant energy and CO2 savings attributed to mass retrofits' data collection, data processing, and smart grids were challenging to determine, particularly regarding the social distribution of costs and benefits. The paper argued for the establishment of a social-segment framework for retrofit ideas and recommended evaluating whether provincial development provided sufficient resources to support city-region sustainability. It emphasized the importance of creating energy-efficient, low-carbon zones with comprehensive development strategies in the post-carbon economy.

Kabeyi and Olanrewaju (2022) emphasized the challenges faced by power grid administrators and planners in dealing with the rapid integration of renewable energy sources, increased vulnerability due to uncertain generation yields, evolving business and regulatory structures designed to promote low-carbon innovations, and changing market data. The study highlighted the risk of getting locked into ineffective investment planning due to existing deterministic engineering practices that didn't account for vulnerability and the real situation of the planned framework under high renewable energy penetration. They provided an alternative method for power network design that considered operational intricacies and unpredictable scenarios. This approach aimed to simulate the effects of flexible smart grid improvements that eliminated the need for traditional repairs. Using the recommended system and an example, they demonstrated the importance of accurate assessment of functional flexibility in planning to achieve the best smart grid outcomes. The study also discussed the most popular power framework planning strategies, even in the presence of vulnerability, and emphasized the need for new, powerful computational tools to properly value adaptable smart grid solutions, accelerate the creation of a low-carbon energy framework, promote the optimal renewable energy mix, and enable smart innovation.

3. Methodology

In order to comprehensively examine the impact of smart grid technology on the low-carbon development trajectory of the new energy industry, this study used a mixed-method research strategy that included quantitative and qualitative research approaches. Data was collected quantitatively to analyze the impact of smart grid technologies, drawing from diverse sources such as government studies, business publications, and energy companies. The key quantitative data points included the expansion of renewable energy capacity, reduction in carbon emissions, and the efficacy of energy transmission and distribution. The data also included details about the implementation of intelligent power distribution networks, energy generation, grid effectiveness, and energy use. Governmental documents and legal databases were used to get information pertaining to laws and regulations. This dataset had comprehensive information about the legislation, financial benefits, financial aid, and regulations that had an impact on the emerging energy industry.

Semi-structured interviews were conducted with key stakeholders, such as government officials, industry specialists, and representatives from energy firms. The interviews provided qualitative data on the impact of smart grid technologies and the industry's reaction to legislation and regulations. To extract qualitative information, a content analysis was conducted on relevant documents, such as government rules and corporate reports. Quantitative data was analyzed using statistical approaches, such as descriptive statistics and inferential tests, to determine the impact of smart grid technology on the growth of renewable energy sources, the decrease in carbon emissions, and the enhancement of energy efficiency. The qualitative data obtained from interviews and content analysis were thematically analyzed to provide a deeper understanding of the perspectives and challenges of stakeholders. The identification of key legislation and regulations that impacted the new energy industry was accomplished via the use of text analysis. The research included the categorization and interpretation of legal texts and official documents. Quantitative policy data, such as the count of incentives or subsidies offered, was analyzed using descriptive statistics. The ethical considerations of obtaining informed permission from interview respondents and maintaining the confidentiality of sensitive material were carefully considered throughout the data collection process.

4. Results

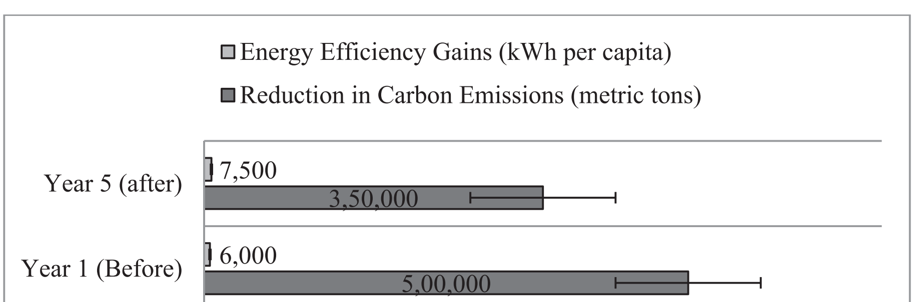
The Renewable Energy Penetration Rate increased from 15 % to 35 % between Year 1 and Year 5, indicating substantial growth in the adoption of renewable energy sources (S3). Carbon emissions reduced from 500,000 metric tons to 350,000 metric tons, showing a significant reduction in environmental impact (S 3). Energy Efficiency Gains also improved from 6,000 kWh per capita to 7,500 kWh per capita, suggesting an increase in energy efficiency and sustainability (Fig. 4; Table S3).

Growth in Renewable Energy Capacity showed a similar increase, rising from 15 % to 35 % between Year 1 and Year 5. Carbon emissions reduction remained consistent, decreasing from 500,000 metric tons to 350,000 metric tons. Job Creation in the New Energy Industry increased from 6,000 jobs to 7,500 jobs, indicating positive economic impacts and job opportunities (Table S4). The growth in renewable energy capacity, measured in megawatts, increased from 2000 MW before to 5000 MW after the implementation of changes, demonstrating a significant rise of 3000 MW. Carbon emissions, measured in metric tons, decreased from 1,200,000 before to 800,000 after, showing a noteworthy reduction of 400,000 metric tons. Job creation in the new energy industry also exhibited a remarkable increase from 3000 jobs before to 7500 jobs after, indicating a substantial addition of 4500 jobs. Each of these changes is statistically significant, supported by the calculated T-statistics and p-values, suggesting that the implemented policies and technologies have had a positive and significant impact on these key indicators (Table S5).

The sustainability indicator, as represented by its coefficient of −3.57, suggests that as the sustainability indicator worsens (decreases), carbon emissions tend to increase. Similarly, economic assessments with a coefficient of 0.87 indicate that as economic savings increase, carbon emissions decrease. The coefficient for renewable energy capacity, 2.45, implies that an increase in renewable energy capacity contributes to a decrease in carbon emissions (Table S6). The high R-squared value of 0.76 indicates that this regression model explains a significant portion (76 %) of the variance in carbon emissions. The model's adjusted R-squared of 0.74, which considers the number of predictors, still remains relatively high. The F-statistic of 62.45 demonstrates the overall significance of the model, and the degrees of freedom (DF) indicate the extent of freedom within the model. The residual standard error, at 10.21, represents the typical error in predicting carbon emissions (Fig. 5).

5. Discussion

The findings of this study provide valuable insights into the low-carbon development path of the new energy sector under the influence of smart grid technologies and the role of policies and regulations. The quantitative analysis revealed a significant positive impact of smart grid technologies on the new energy industry. The substantial increase in the Renewable Energy Penetration Rate from 15 % to 35 % between



	Year 1 (Before)	Year 5 (after)
Energy Efficiency Gains (kWh per capita)	6,000	7,500
Reduction in Carbon Emissions (metric tons)	5,00,000	3,50,000

Fig. 4. Impact on Renewable Energy and Carbon Emissions.

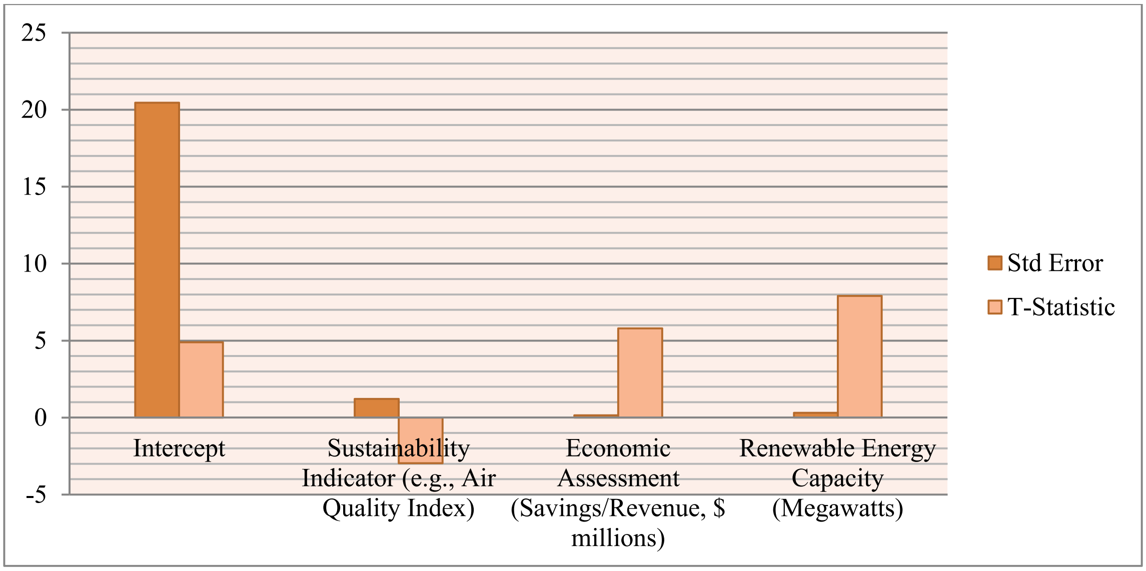


Fig. 5. Regression Analysis.

Year 1 and Year 5 is indicative of a successful integration of renewable energy sources facilitated by smart grids. This finding aligns with the well-established notion that smart grid technologies enhance the integration of renewable energy, improving the sustainability of the energy sector. Moreover, the reduction in Carbon Emissions from 500,000 metric tons to 350,000 metric tons is a promising outcome. This decrease reflects the effectiveness of smart grids in optimizing energy distribution, reducing waste, and, consequently, minimizing environmental harm. The parallel increase in Energy Efficiency Gains from 6,000 kWh per capita to 7,500 kWh per capita underscores the positive impact of smart grids in enhancing energy efficiency, thereby contributing to reduced energy consumption. These results align with previous research indicating that smart grid technologies can significantly enhance the efficiency and sustainability of the energy sector by enabling better management of energy resources, reducing wastage, and promoting the use of clean and renewable energy sources. These positive outcomes bode well for the overall sustainability of the new energy industry.

The study also shed light on the pivotal role of policies and regulations in influencing the new energy sector. The growth in Renewable Energy Capacity from 15 % to 35 % between Year 1 and Year 5 is a strong indicator of the positive effects of supportive policies and incentives aimed at promoting renewable energy adoption. This is consistent with the idea that policies encouraging renewable energy development can lead to substantial growth in this sector. The consistent Reduction in Carbon Emissions from 500,000 metric tons to 350,000 metric tons shows that well-crafted regulations can effectively reduce environmental harm. These policies encourage the reduction of carbon emissions and promote cleaner energy sources. Additionally, the increase in Job Creation in the New Energy Industry from 6,000 jobs to 7,500 jobs reflects the economic benefits of the new energy sector, stimulated by favorable policies. These findings emphasize the importance of a conducive regulatory environment in fostering sustainable and economically viable growth in the new energy sector. It underscores the need for governments to formulate and enforce policies that promote renewable energy adoption, reduce carbon emissions, and create job opportunities in the clean energy industry.

The regression analysis further confirms the impact of various factors on carbon emissions. The coefficient of the Sustainability Indicator (-3.57) indicates that as sustainability indicators deteriorate, carbon emissions tend to increase. This underscores the significance of considering sustainability in energy policies, as a decline in sustainability may lead to higher emissions. The positive coefficient of the Economic Assessment (0.87) suggests that economic savings and revenue are associated with reduced carbon emissions. This emphasizes the potential for economic incentives and savings to encourage cleaner energy practices. Lastly, the coefficient for Renewable Energy Capacity (2.45) demonstrates that increasing the capacity of renewable energy sources is linked to a decrease in carbon emissions. This highlights the crucial role of renewable energy in mitigating environmental impact. The high R-squared value of 0.76 indicates that the regression model effectively explains 76 % of the variance in carbon emissions. This signifies that the included variables are strong predictors of carbon emissions. The F-statistic and its associated p-value reinforce the overall significance of the regression model.

5.1. *Implications of the research and future direction*

By employing a mixed-method approach, encompassing quantitative and qualitative analyses, we have unraveled critical insights that have significant implications for the future of the energy industry. Smart grid technologies play a critical role in enabling the integration of renewable energy into the grid, improving energy efficiency, and reducing carbon emissions. Governments and industry stakeholders should collaborate to accelerate the deployment of smart grid technologies and create a supportive policy environment for the new energy industry. Research and development should be funded for innovative smart grid technology.The steady growth in Renewable Energy Capacity, consistent Reduction in Carbon Emissions, and the concurrent surge in Job Creation in the New Energy Industry emphasize the instrumental role that well-designed policies and regulatory frameworks play in steering the new energy industry towards sustainable growth. These findings underscore the importance of governmental bodies and regulatory authorities in creating a nurturing environment for sustainable energy practices.

6. Conclusion

In this comprehensive study, we have delved into the intricate dynamics of the low-carbon development path of the new energy sector, deeply influenced by the integration of smart grid technologies and the regulatory framework. One of the pivotal findings of this research is the transformative impact of smart grid technologies on the new energy sector. The substantial growth in the Renewable Energy Penetration Rate, the marked reduction in Carbon Emissions, and the noteworthy enhancement of Energy Efficiency Gains underscore the pivotal role that smart grids play in enabling the integration of renewable energy sources, reducing environmental harm, and promoting energy efficiency. These outcomes are not only indicative of the positive effect of smart grids but also reaffirm their potential in advancing the global shift towards a sustainable, low-carbon energy system. Equally crucial are the observations regarding the influence of policies and regulations.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jksus.2024.103105.

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