STRATEGIC MAINTENANCE AND TECHNOLOGICAL INNOVATION AS RESPONSES TO STRUCTURAL CHALLENGES IN RENEWABLE ENERGY PRODUCTION CHAINS

MANUTENÇÃO ESTRATÉGICA E INOVAÇÃO TECNOLÓGICA COMO RESPOSTAS AOS DESAFIOS ESTRUTURAIS NAS CADEIAS PRODUTIVAS DE ENERGIA RENOVÁVEL

MANTENIMIENTO ESTRATÉGICO E INNOVACIÓN TECNOLÓGICA COMO RESPUESTAS A LOS DESAFÍOS ESTRUCTURALES EN LAS CADENAS PRODUCTIVAS DE ENERGÍA RENOVABLE

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ABSTRACT

Renewable energy production chains play a central role in the global energy transition, as they are essential for reducing greenhouse gas emissions and promoting a more sustainable energy matrix. However, the expansion and consolidation of these chains have revealed a set of structural challenges related to asset reliability, operational complexity, and the long-term sustainability of energy infrastructures. In this context, strategic maintenance and technological innovation emerge as critical elements for ensuring the resilience, efficiency, and competitiveness of renewable energy systems. A qualitative approach was adopted, as it is suitable for exploring phenomena that require a deeper understanding of contexts,

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processes, and interactions. Regarding methodological procedures, the research was classified as bibliographic. This type of procedure is based on the careful analysis of previously published scientific works, which constitutes one of the foundations of scientific knowledge construction. The general objective of this study is to analyze how strategic maintenance and technological innovation can function as effective responses to the structural challenges of renewable energy production chains, contributing to increased operational reliability, asset sustainability, and competitiveness within the energy sector. According to the study, maintenance management, when effectively integrated with new technologies and a comprehensive view of the production chain, represents a key factor in increasing operational reliability. Furthermore, efficient management enables more conscious use of resources and contributes to strengthening the sustainability of assets linked to electric energy generation. The relationship between maintenance management and the implementation of technological solutions proves to be highly beneficial for the energy sector, resulting in stronger and more effective performance.

Keywords: Strategic Maintenance. Technological Innovation. Renewable Energy. Operational Reliability. Sustainability.

RESUMO

As cadeias produtivas de energia renovável desempenham um papel central na transição energética global, pois são essenciais para reduzir as emissões de gases de efeito estufa e promover uma matriz energética mais sustentável. No entanto, a expansão e consolidação dessas cadeias revelaram um conjunto de desafios estruturais relacionados à confiabilidade dos ativos, à complexidade operacional e à sustentabilidade de longo prazo das infraestruturas energéticas. Nesse contexto, a manutenção estratégica e a inovação tecnológica emergem como elementos críticos para garantir a resiliência, a eficiência e a competitividade dos sistemas de energia renovável. Adotou-se uma abordagem qualitativa, pois é adequada para explorar fenômenos que exigem uma compreensão mais profunda de contextos, processos e interações. Quanto aos procedimentos metodológicos, a pesquisa foi classificada como bibliográfica. Esse tipo de procedimento baseia-se na análise cuidadosa de trabalhos científicos previamente publicados, o que constitui um dos fundamentos da construção do conhecimento científico. O objetivo geral deste estudo é analisar como a manutenção estratégica e a inovação tecnológica podem funcionar como respostas eficazes aos desafios estruturais das cadeias produtivas de energia renovável, contribuindo para o aumento da confiabilidade operacional, da sustentabilidade dos ativos e da competitividade no setor energético. De acordo com o estudo, a gestão da manutenção, quando efetivamente integrada às novas tecnologias e a uma visão abrangente da cadeia produtiva, representa um fator-chave para o aumento da confiabilidade operacional. Além disso, uma gestão eficiente possibilita um uso mais consciente dos recursos e contribui para o fortalecimento da sustentabilidade dos ativos vinculados à geração de energia elétrica. A relação entre a gestão da manutenção e a implementação de soluções tecnológicas mostra-se altamente benéfica para o setor energético, resultando em um desempenho mais robusto e eficaz.

Palavras-chave: Manutenção Estratégica. Inovação Tecnológica. Energia Renovável. Confiabilidade Operacional. Sustentabilidade.

RESUMEN

Las cadenas productivas de energía renovable desempeñan un papel central en la transición energética global, ya que son esenciales para reducir las emisiones de gases de efecto invernadero y promover una matriz energética más sostenible. Sin embargo, la expansión y consolidación de estas cadenas revelaron un conjunto de desafíos estructurales relacionados con la confiabilidad de los activos, la complejidad operativa y la sostenibilidad a largo plazo de las infraestructuras energéticas. En este contexto, el mantenimiento estratégico y la innovación tecnológica emergen como elementos críticos para garantizar la resiliencia, la eficiencia y la competitividad de los sistemas de energía renovable. Se adoptó un enfoque cualitativo, ya que es adecuado para explorar fenómenos que requieren una comprensión más profunda de contextos, procesos e interacciones. En cuanto a los procedimientos metodológicos, la investigación fue clasificada como bibliográfica. Este tipo de procedimiento se basa en el análisis cuidadoso de trabajos científicos previamente publicados, lo que constituye uno de los fundamentos de la construcción del conocimiento científico. El objetivo general de este estudio es analizar cómo el mantenimiento estratégico y la innovación tecnológica pueden funcionar como respuestas efectivas a los desafíos estructurales de las cadenas productivas de energía renovable, contribuyendo al aumento de la confiabilidad operativa, la sostenibilidad de los activos y la competitividad dentro del sector energético. Según el estudio, la gestión del mantenimiento, cuando se integra eficazmente con nuevas tecnologías y con una visión integral de la cadena productiva, representa un factor clave para incrementar la confiabilidad operativa. Además, una gestión eficiente permite un uso más consciente de los recursos y contribuye al fortalecimiento de la sostenibilidad de los activos vinculados a la generación de energía eléctrica. La relación entre la gestión del mantenimiento y la implementación de soluciones tecnológicas resulta altamente beneficiosa para el sector energético, dando lugar a un desempeño más sólido y eficaz.

Palabras clave: Mantenimiento Estratégico. Innovación Tecnológica. Energía Renovable. Confiabilidad Operativa. Sostenibilidad.

1 INTRODUCTION

The growth of renewable energy sources has become a central pillar of energy transition agendas, driven by the urgency to diversify the electricity matrix, reduce emissions, and enhance energy security. In this context, the production chains associated with these sources have assumed a strategic role, as they connect industrial, technological, and operational processes that are essential for the implementation and operation of power plants. However, the rapid expansion of the sector has also exposed structural challenges that directly affect business reliability, efficiency, and sustainability.

Among these challenges are infrastructure constraints, asset management issues, and the integration of different links within production chains. Within the current context, strategic maintenance and technological innovation emerge as key approaches to addressing the operational and structural demands of the sector, improving plant performance, reducing costs, and increasing the competitiveness of renewable energy sources in an energy landscape marked by growing complexity and continuous change.

A qualitative approach was adopted, as it is suitable for exploring phenomena that require a deeper understanding of contexts, processes, and interactions. Regarding methodological procedures, the research was classified as bibliographic. This type of procedure is based on the careful analysis of previously published scientific works, which constitutes one of the foundations of scientific knowledge construction.

The general objective of this study is to analyze how strategic maintenance and technological innovation can function as effective responses to the structural challenges of renewable energy production chains, contributing to increased operational reliability, asset sustainability, and competitiveness within the energy sector.

The following specific objectives were defined: to examine the main structural challenges affecting renewable energy production chains, with emphasis on their impacts on plant operation and maintenance; to evaluate models and practices of strategic maintenance applied to renewable energy plants, considering their effects on cost reduction, increased reliability, and extension of asset service life; and to investigate the role of technological innovation in improving maintenance processes and strengthening efficiency, safety, and structural resilience in renewable energy plants.

The article is organized into four sections. The first section presents the introduction, which contextualizes the topic and defines the objectives of the study. The second section addresses the methodology, detailing the approach and procedures adopted. The third section focuses on the theoretical framework, discussing structural challenges, strategic maintenance, and technological innovation in renewable energy production chains. The fourth section presents the final considerations, summarizing the main findings of the study and offering concluding reflections.

2 METHODOLOGY

The methodology adopted in this study was defined based on the need to systematically and interpretively understand the relationships between strategic maintenance, technological innovation, and the structural challenges of renewable energy production chains. Considering the complexity of the topic and its positioning within a field characterized by multiple technical, organizational, and structural dimensions, a methodological framework was selected that enables an integrated analysis of concepts, models, and evidence found in the scientific literature.

A qualitative approach was employed, as it is appropriate for the exploration of phenomena that require a deeper understanding of contexts, processes, and interactions. According to Guerra et al. (2024), the qualitative approach occupies a prominent position in contemporary scientific research by enabling consistent interpretations of complex phenomena and contributing to knowledge construction across different fields. Yin (2016) clearly explains that this type of approach allows for the investigation of relationships and meanings that cannot be fully captured through strictly quantitative methods. This aspect is crucial for an in-depth analysis, as the chosen methodology supports a more detailed and interpretative examination of the data.

Within the context of global scientific research, qualitative methodology has been widely valued and recognized for its ability to structure theoretical analyses that are both robust and coherent. This is particularly evident in fields such as management, technology, and sustainability. The qualitative approach enables a deeper understanding of the phenomena under investigation, thereby making a significant contribution to the development of practices and solutions in these areas. According to Pereira et al. (2018), this approach is especially beneficial because it promotes the organization and systematization of existing knowledge. Such systematization not only facilitates the establishment of links among different scientific contributions but also allows for the identification of theoretical convergences that are essential for the advancement of research in this field.

With regard to methodological procedures, the research was classified as bibliographic. This type of procedure is based on the careful analysis of previously published scientific works, which constitutes one of the pillars of scientific knowledge construction. According to Pereira et al. (2018), bibliographic research is capable of consolidating theoretical and methodological frameworks by gathering and interpreting significant contributions on a specific topic. Yin (2016) adds that this method enhances the analytical robustness of research by grounding discussions in well-established theories.

The corpus of scientific works analyzed consisted of scientific articles, monographs, dissertations, theses, and books addressing strategic maintenance, technological innovation, and renewable energy production chains. It is noteworthy that most of the analyzed works were published from 2023 onward, which ensures the contemporaneity of the discussions and the alignment of the study with recent debates in the scientific field, in accordance with the methodological guidelines discussed by Guerra et al. (2024), Pereira et al. (2018), and Yin (2016).

3 THEORETICAL FRAMEWORK

The theoretical framework was organized into three complementary topics, enabling a gradual and interconnected understanding of the subject under analysis. The first topic, **3.1 Structural challenges in renewable energy production chains**, examines the technical, operational, and systemic constraints that most significantly affect the operation and maintenance of power plants. Subsequently, topic **3.2 Strategic maintenance in renewable energy plants** presents the main concepts, models, and maintenance management practices, with emphasis on preventive, predictive, and condition-based approaches. Finally, topic **3.3 Technological innovation applied to maintenance and structural resilience** explores how emerging technologies can strengthen asset efficiency, safety, and resilience, reinforcing the link between strategic maintenance and technological innovation within renewable energy production chains.

3.1 STRUCTURAL CHALLENGES IN RENEWABLE ENERGY PRODUCTION CHAINS

The structural obstacles affecting production chains associated with renewable energy in Brazil become evident through their direct impact on the efficient operation and adequate maintenance of power plants, particularly in contexts of accelerated expansion of installed capacity. This situation can generate a range of complications that require targeted attention and specific strategies to ensure optimized plant performance and the ability to meet the growing demand for sustainable energy sources.

The International Energy Agency (IEA, 2023) reported that the significant increase in the integration of intermittent renewable sources, such as solar and wind power, has intensified the need to balance supply and demand in real time. This condition often leads to intentional generation curtailment in order to prevent grid instability and overloads. Under such circumstances, there is a clear need to incorporate disruptive technologies aimed at enhancing safety and operational reliability in renewable energy generation plants.

Specialized literature emphasizes that the consolidation of production chains occurs asymmetrically, facing challenges such as limited industrial capacity, strong dependence on foreign technologies, and vulnerabilities in logistics systems. These factors negatively affect the operational efficiency of companies operating in this sector, particularly in wind and solar energy segments (Cella, Cardoso, & Cardoso, 2025; Pan et al., 2024).

From a more technical and operational perspective, plant infrastructure faces bottlenecks related to curtailment, shortages of essential components, and progressive asset degradation. These issues directly impact reliability and availability indicators, thereby requiring maintenance strategies that are increasingly aligned with the realities of production chains. As noted by Paixão and Abaide (2025), such challenges highlight the urgency of more effective integration between energy planning, system operation, and maintenance support policies.

The interconnection between generation, transmission, and maintenance represents another critical aspect of renewable energy production chains. Rapid expansion of generation capacity without corresponding investments in transmission infrastructure and operational support systems exacerbates losses, operational constraints, and recurrent failures. Recent research indicates that the lack of systemic coordination undermines not only technical efficiency but also the sustainability objectives inherently associated with the energy transition (Santos et al., 2025).

Beyond technical issues, structural challenges also encompass systemic and environmental dimensions that affect the entire production chain. Component manufacturing, implementation logistics, and maintenance activities generate significant environmental impacts and must be more closely aligned with sustainability and governance guidelines. Nunes et al. (2025) and Farias, Martins, and Cândido (2021) emphasize that balancing operational performance with socioenvironmental responsibility remains a persistent challenge for the sector.

In this context, Table 1 summarizes the main structural bottlenecks identified in the literature and their respective impacts on power plant infrastructure.

Table 1

Structural bottlenecks in renewable energy production chains and their impacts on power plant infrastructure

Dimension	Identified bottlenecks	Impacts on operation and maintenance
Technical	Asset aging and technological limitations	Reduced reliability and increased failure rates
Operational	Curtailment and unavailability of components	Generation losses and increased maintenance costs
Systemic	Fragility in generation–transmission–maintenance integration	Operational constraints and lower overall efficiency
Environmental	Environmental pressures along the production chain	Need for compliance with sustainability standards

Source: Cella, Cardoso e Cardoso (2025); Farias, Martins e Cândido (2021); Nunes et al. (2025); Paixão e Abaide (2025); Pan et al. (2024); Santos et al. (2025).

The identified bottlenecks reflect interactions among technical, operational, and institutional factors rather than merely isolated issues. The lack of effective integration among the links of the production chain increases operational risks and hinders the implementation of maintenance strategies aligned with the growing demands for reliability and sustainability within the energy sector (Paixão; Abaide, 2025).

Ultimately, overcoming these obstacles requires a systemic approach in which power plant maintenance is understood as an essential component of the production chain, rather than merely a support activity. The reviewed literature consistently indicates that strengthening production chains, together with technological innovation and coordination among the various segments of the sector, represents an indispensable pathway for reducing structural vulnerabilities and ensuring greater competitiveness for renewable energy sources in the current energy landscape (Cella; Cardoso; Cardoso, 2025; Pan et al., 2024).

3.2 STRATEGIC MAINTENANCE IN RENEWABLE ENERGY PLANTS

Asset management in renewable energy plants has placed strategic maintenance at the center of attention, primarily due to increasing technological complexity and the need to maintain high levels of operational reliability. As highlighted by Viana (2020), maintenance management has evolved from a corrective and reactive function to an integral part of organizational planning, directly influencing costs, system performance, and generation continuity.

In renewable energy plants, preventive maintenance planned through structured models is a common practice aimed at minimizing unexpected failures and controlling component degradation. According to Araújo (2025), the adoption of a formal maintenance management system increases the predictability of interventions, resulting in more efficient resource allocation and a reduction in unplanned outages, which is particularly critical for wind and solar energy projects.

Predictive maintenance, in turn, significantly enhances asset monitoring by integrating advanced inspection techniques and conducting detailed analyses of operational data generated during their application. This approach enables a more accurate understanding of asset conditions and allows interventions to be carried out in a more strategic manner. According to Gomes et al. (2025), the use of drones combined with multiple testing methods and digital technologies has proven highly effective for the early detection of anomalies. This not only raises operational safety standards but also improves overall plant efficiency. Furthermore, this approach supports more precise, data-driven decision-making when planning required interventions.

With the advent of Industry 4.0, predictive and prescriptive maintenance strategies have been further strengthened, as algorithms and intelligent systems increasingly guide decision-making processes. According to Machado et al. (2023), these practices represent an evolution of traditional maintenance models, as they incorporate real-time data and predictive analytics, leading to more reliable systems and more efficient asset life cycle management. In comparison with the main maintenance approaches applied in renewable energy plants, Table 2 provides an overview of their key characteristics and effects.

Table 2

Strategic maintenance approaches in renewable energy plants and their main effects

Maintenance approach	**Main characteristics**	**Effects on costs, reliability, and service life**
Preventive	Scheduled and periodic interventions	Reduction in failures and greater operational predictability
Predictive	Continuous monitoring and data analysis	Early identification of failures and lower corrective costs
Condition-based	Interventions guided by asset condition	Extension of service life and optimization of resources
Prescriptive	Use of intelligent systems and algorithms	Decision support and increased systemic reliability

Source: Viana (2020); Araújo (2025); Gomes et al. (2025); Machado et al. (2023).

As with other generation sources, maintenance in renewable energy generation systems must also be planned in accordance with market conditions and the operation of the electrical system. In decentralized environments, coordination among generation, maintenance, and commercialization is a determining factor in terms of cost efficiency and supply reliability (Paula, 2021).

In this context, evolutionary strategies and optimization techniques have increasingly been applied to the maintenance planning of generation units. As demonstrated by Rodrigues, Assis, and Resende (2020), these strategies make it possible to reconcile technical and operational constraints, resulting in more efficient scheduling of interventions with reduced impacts on asset availability.

Finally, multi-objective optimization techniques enhance the ability to evaluate trade-offs in maintenance management. Sadeghian et al. (2019) indicate that jointly assessing technical, economic, and operational criteria leads to more balanced decision-making, thereby strengthening strategic maintenance as a fundamental element for operational sustainability and the competitiveness of renewable energy plants.

3.3 TECHNOLOGICAL INNOVATION APPLIED TO MAINTENANCE AND STRUCTURAL RESILIENCE

A report by the United Nations Children's Fund (UNICEF, 2023) cited projections by the International Energy Agency indicating that solar photovoltaic and wind energy would account for nearly 95 percent of global renewable capacity additions by 2027, while technological challenges and limited policy support have slowed the expansion of hydropower, bioenergy, geothermal, and ocean energy technologies.

In turn, studies by Hille, Althammer, and Diederich (2020) highlight the central role of technological innovation in advancing the renewable energy sector, enhancing its competitiveness and promoting sustainable business models that benefit the respective production chains. In this sense, emerging technologies such as advanced energy storage systems, smart grids, and the digitalization of energy systems have enabled greater efficiency in the generation, distribution, and consumption of renewable energy.

Technological innovation in maintenance and structural resilience of renewable energy plants is directly linked to a broader transformation of productive and energy systems. As noted by Barbieri (2024), the implementation of innovations aligned with sustainable development reshapes industrial processes by integrating operational efficiency, environmental responsibility, and the rational use of resources, aspects that are closely connected to maintenance management in energy assets.

Within the electric power sector, digitalization and the pursuit of more reliable systems have accelerated technological innovation. According to Cardoso, Camilo, and Picolo (2024), among the most significant advances are digital sensors, continuous monitoring systems, and data analytics platforms, which provide greater visibility into the operational and structural conditions of power plants. These technologies enable more consistent maintenance planning and more robust structural risk management.

The development and advancement of innovations related to renewable energy sources in Brazil demonstrate a continuous and gradual process of integrating technological solutions aimed primarily at improving efficiency and ensuring asset safety within the sector. This trajectory has proven relevant in the construction of a more sustainable and reliable energy environment. Gonsales (2020) emphasizes that, in the wind and solar energy segments, the implementation of automated monitoring systems combined with data analysis plays a significant role in enabling the anticipation of potential failures and improving maintenance-related processes. This practice, in turn, has a direct and positive impact on the operational stability of power plants, ensuring more efficient and reliable performance.

From a strategic perspective, Marques (2022) argues that disruptive technologies in the electric power sector can enhance the adaptive resilience of production chains. Such innovations integrate automation, digitalization, and more intelligent asset management, leading to substantive transformations in sector operations. With regard to maintenance, the application of innovations in renewable energy plants is essential, as they significantly increase the structural resilience of these facilities, reducing exposure to critical scenarios. Moreover, these innovations also enhance operational safety, making operations more secure and reliable when facing emerging challenges. In summary, Table 3 presents the main technologies applied in maintenance processes and explains how each affects the structural resilience of renewable energy plants.

Table 3

Technologies applied to maintenance and their effects on the structural resilience of renewable energy plants

Technology	Application in maintenance	Contributions to efficiency and safety
Digital sensors	Continuous monitoring of components	Early detection of structural failures
Structural monitoring systems	Monitoring of asset performance	Risk reduction and increased reliability
Data analysis	Processing of large volumes of information	Decision support and optimization of interventions

Technology	Application in maintenance	Contributions to efficiency and safety
Automation	Execution and control of operational processes	Greater efficiency and standardization of operations

Source: Barbieri (2024); Cardoso, Camilo e Picolo (2024); Gonsales (2020); Marques (2022).

The adoption of these technologies also depends on institutional conditions and policies that encourage innovation. Negri (2018) emphasizes that the consolidation of favorable environments for innovation in Brazil requires coordination among the State, the productive sector, and the scientific system, thereby creating conditions that allow technological solutions to move from the experimental stage to effective applications within renewable energy production chains.

The obstacles that arise during the energy transition further underscore the importance of technological innovation, which serves as a crucial support for ensuring the maintenance and structural resilience of power plants throughout this process. Thus, amid adversity, innovation emerges as a vital element for the effective and sustainable operation of facilities. Santos et al. (2024) argue that, in order to increase the renewability of the electric power matrix, it is necessary to rely on systems that are both safer and more efficient. In this context, the synergy among the technology employed, appropriate maintenance practices, and effective asset management is a determining factor for ensuring that renewable energy production chains remain competitive and stable. This connection is fundamental for advancing toward a sustainable and innovative energy future.

4 FINAL CONSIDERATIONS

Renewable energy production chains play a highly significant role in the energy transition. At the same time, they bring to light a series of structural challenges that directly affect areas such as operation, maintenance, and asset sustainability. Addressing these challenges is essential to ensure that renewable energy systems operate effectively and responsibly, taking into account current and future demands for energy production and consumption. The growing complexity of the technologies used in power plants, combined with the need to maintain high operational reliability, highlights the importance of integrated approaches. In this context, the combination of strategic maintenance and technological innovation emerges as a robust and effective response to the current demands and requirements of the energy sector. Accordingly, it is essential that these two areas operate in an integrated manner to ensure that energy operations are not only efficient but also safe and continuous.

Throughout the development of this research, all proposed objectives were fully achieved. The analysis conducted made it possible to examine the main structural challenges faced by renewable energy production chains, to evaluate models and practices of strategic maintenance applied to power plants, and to investigate the role of technological innovation in improving maintenance processes, as well as in strengthening efficiency, safety, and structural resilience within these enterprises.

A detailed analysis of the challenges related to the structural conditions of power plants reveals the presence of several bottlenecks that directly affect plant reliability. These bottlenecks can be classified as technical, operational, and systemic in nature. This situation largely results from factors such as infrastructure limitations, equipment and asset aging, and weaknesses in the integration among generation, transmission, and maintenance processes. These elements are essential for understanding the current condition of power plants and how such factors interact to affect overall performance. With regard to strategic maintenance, studies indicate that the implementation of preventive, predictive, and condition-based maintenance leads to a significant and positive reduction in operational costs. These approaches also improve system availability, enabling more efficient and uninterrupted operation. Another relevant benefit is the extension of asset service life, referring to the equipment and components used in operations. Consequently, the adoption of these strategies becomes indispensable for optimizing resources and improving organizational performance. In terms of technological innovation, the adoption of digital sensors, structural monitoring systems, data analysis tools, and automation technologies was found to substantially enhance structural safety and operational efficiency. Moreover, this technological convergence boosts the competitiveness of production chains, allowing companies to stand out in an increasingly challenging and dynamic market.

In a logical and integrated manner, the evidence indicates that the combination of a solid maintenance strategy and technological innovation constitutes an indispensable and structuring factor for addressing the various adversities faced by renewable energy production chains. This connection is vital for enabling companies to navigate challenges and remain competitive in a constantly evolving market. According to the study, maintenance management, when effectively integrated with new technologies and a comprehensive view of the production chain, represents a key factor in increasing operational reliability. Furthermore, efficient management enables more conscious use of resources and contributes to strengthening the sustainability of assets linked to electric energy generation. The relationship between maintenance management and the implementation of technological solutions proves to be highly beneficial for the energy sector, resulting in stronger and more effective performance.

In conclusion, future research is recommended to examine the practical implementation of these methodologies across different regional contexts and types of power plants. This includes the need to analyze the interaction among public policies, existing regulatory models, and the various maintenance strategies adopted. Such analyses may provide a more comprehensive understanding of the relationships and dynamics that influence the effectiveness of these systems in diverse scenarios. Studies aimed at quantifying outcomes across multiple domains, including economic, operational, and environmental aspects, throughout the entire asset life cycle, may further enhance understanding of the impacts of planned maintenance and technological innovation on renewable energy supply chains. This approach has the potential to strengthen and complement the analyses developed in this study.

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