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Decarbonization And Sustainability: The Role of Artificial Intelligence in the Integration of Renewable Energy Sources

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ABSTRACT
The growing demand for sustainable energy solutions drives the development of technologies that enable the transition toward clean and efficient energy matrices. In this context, artificial intelligence has emerged as a strategic tool to optimize the management of renewable sources, contribute to decarbonization, and enhance the efficiency of energy systems. The present research adopted a qualitative approach, focusing on the critical analysis of content from diverse sources, with the aim of understanding the role of artificial intelligence in the assimilation of renewable energy sources within energy transition contexts. The general objective of this study

was to analyze how the application of artificial intelligence can contribute to the efficient integration of renewable energy sources in energy transition scenarios, with an emphasis on decarbonization and the promotion of sustainability. Conclusively, the findings support that the implementation of artificial intelligence methodologies is closely related to the improvement of energy management, fostering greater predictability, operational efficiency, and adaptability to conditions of climate variability and demand. The intersection of technical, environmental, and political factors revealed that the incorporation of renewable sources requires not only sophisticated computational solutions but also institutional harmonization that enables sustainable innovations in the production, distribution, and consumption of energy in the medium and long term.

***Keywords**: Energy solutions; Decarbonization; Renewable sources; Artificial intelligence.*

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I. INTRODUCTION

In recent decades, the global energy sector has faced the challenge of aligning with international environmental commitments, particularly regarding the reduction of greenhouse gas emissions and the mitigation of the impacts stemming from the intensive use of fossil fuels. In this context, the energy transition stands out as a strategic process aimed at the gradual replacement of traditional energy matrices with renewable and sustainable sources. Such a structural transformation requires not only investment in innovative technologies but also the restructuring of management models, the formulation of public policies, and the development of mechanisms for systemic integration. The advancement of digital technologies—especially solutions grounded in artificial intelligence—has played a key role in this process, providing tools for monitoring, forecasting, decision-making, and optimizing the use of clean energy sources in diverse contexts.

Simultaneously, the decarbonization of the energy economy is a strategic priority on global climate agendas. Energy efficiency, diversification of sources, and the coherent integration of sustainable systems are essential to ensuring a transition that is safe, economically viable, and environmentally balanced. In this scenario, artificial intelligence plays a significant role by enabling the analysis of extensive real-time datasets, the identification of operational patterns, and the automation of complex decision-making processes. The current discourse on energy sustainability, therefore, requires an interdisciplinary approach that considers both technological advancements and the socio-environmental and regulatory challenges involved in altering existing energy matrices.

This research employed a qualitative approach, focusing on the critical analysis of content from diverse sources, with the aim of understanding the role of artificial intelligence in the assimilation of renewable sources within the context of the energy transition. The general objective of the study was to analyze how the application of artificial intelligence can contribute to the efficient integration of renewable energy sources in energy transition scenarios, with an emphasis on decarbonization and the promotion of sustainability.

The specific objectives established were as follows: (a) to investigate the main applications of artificial intelligence in the management and optimization of renewable energy systems; (b) to identify the impacts of decarbonization on energy efficiency and the reduction of carbon emissions; and (c) to assess the challenges and potential of the intelligent integration of renewable sources within the context of sustainable energy transition.

This investigation was structured into four main sections. The first section presents the introduction, which contextualizes the topic, justifies its relevance, and outlines the research objectives. The second section, dedicated to materials and methods, details the qualitative approach adopted, the methodological procedures implemented, and the analytical strategies employed. The third section, comprising the theoretical framework, addresses the main conceptual axes: the applications of artificial intelligence in renewable energy, the relationship between decarbonization and energy efficiency, and the strategic aspects of the intelligent integration of sustainable sources. Finally, the fourth section presents the concluding remarks, summarizing the findings and highlighting opportunities for future research.

II. MATERIAL AND METHODS

The present study employed a qualitative approach, focusing on the critical analysis of content from various sources, with the aim of understanding the role of artificial intelligence in the assimilation of renewable sources within energy transition contexts. The theoretical foundation is based on the integration of bibliographic and documentary research, including scientific articles, technical reports, and official documents, in line with Cavalcante and Oliveira (2020), who emphasize the relevance of systematic literature reviews for the construction of interdisciplinary knowledge. A total of 34 works were analyzed, comprising indexed journal articles, papers presented at scientific events, and official documents from national and international organizations. This substantial body of material enabled a more precise mapping of the various theoretical and practical perspectives relevant to the topic under examination, thereby conferring greater robustness to the argumentative foundation of the research.

The method used for data processing and organization was thematic analysis, as outlined by Braun and Clarke (2014), given its suitability for identifying significant patterns and recurring discursive elements in diverse materials. This approach allows for the interpretative organization of data obtained from multiple sources, as highlighted by Simões, Moura, and Silva (2023) in their analysis of documentary research in administrative environments. The development of three analytical tables was employed as a strategy for content systematization, enabling the identification of significant categories and the comparison of international and national perspectives concerning the interaction between artificial intelligence, sustainability, and energy transition. The tables also proved effective in synthesizing the main regulatory and technical milestones pertinent to the subject.

In accordance with the methodological guidelines proposed by Bandeira (2022), an analysis plan focused on the description and interpretation of data was selected, in alignment with the established objectives. The author emphasizes that, in qualitative research, a clear distinction between descriptive and interpretative levels is crucial for the validity of the inferences generated. In this regard, the thematic analysis was conducted in three phases: exploratory reading of the selected materials, categorization according to analytical axes, and interpretation based on the previously established theoretical frameworks. The diversity of sources examined facilitated a comprehensive understanding of the phenomenon under study, allowing for the integration of different scientific and institutional approaches to the strategic application of artificial intelligence in the management of sustainable energy models.

III. THEORETICAL FRAMEWORK

The theoretical foundation of this study was organized into three interconnected topics, aiming to provide a systematic and cohesive understanding of the subject under analysis. The first axis, *"Artificial Intelligence in Renewable Energy Systems"* (3.1), addresses the applications and contributions of artificial intelligence–based systems for the supervision, forecasting, and maximization of clean energy source performance. The second topic, entitled *"Decarbonization and Energy Efficiency"* (3.2), examines fundamental concepts, policies, and strategies aimed at reducing carbon emissions and promoting more efficient energy systems, situating these practices within the context of global transformations. Finally, the third axis, *"Intelligent Integration of Renewable Sources in the Energy Transition"* (3.3), analyzes the challenges and solutions for interconnecting various sustainable technologies into smart energy grids, drawing upon technical, environmental, and regulatory perspectives. This thematic and analytical structuring facilitated the connection of the main theoretical frameworks and enabled the construction of a consistent foundation for the development of the proposed analysis.

3.1 Artificial Intelligence in Renewable Energy Systems

Energy policy decision-makers must formulate measures to promote sustainable technologies as they reach the market. Over time, the development of such technologies tends to reduce costs, making them increasingly competitive (IEA, 2021). In this convergence, the application of artificial intelligence (AI) methods in renewable energy systems has generated innovative responses to address challenges related to variability, efficiency, and reliability. Tools such as artificial neural networks, genetic algorithms, fuzzy logic, and hybrid models have been extensively employed in the modeling, forecasting, and regulation of electricity generation from sources such as solar, wind, and biomass. Garud, Jayaraj, and Lee (2021) conducted a comprehensive review of modeling methodologies for photovoltaic systems, highlighting how different AI techniques can be integrated to enhance predictive accuracy and energy management. Aguiar-Furucho et al. (2024) investigated the use of artificial neural networks for solar irradiance forecasting, emphasizing their relevance in the educational context focused on renewable energy. These approaches, in addition to being strictly predictive techniques, enable the adoption of agile and adaptive response mechanisms to climatic changes and fluctuating demand, fostering stability and flexibility within the energy matrix.

With the increasing complexity of interconnected energy systems, the application of artificial intelligence has also expanded to the identification, analysis, and assessment of failures. Liu, Hajj, and Bao (2022) examined the role of intelligent robotics in assessing damage to offshore wind turbines, highlighting how intelligent sensors and learning algorithms can prevent severe failures and improve predictive maintenance. This type of application underscores the importance of integrating AI not only in generation but also in the operational management of renewable assets. Similarly, Kamio et al. (2024) proposed a computational framework for power quality control and monitoring, emphasizing Industry 4.0 and integration with renewable sources. The combination of artificial intelligence and cyber-physical systems enables more effective and cohesive management of clean energy production and distribution, aligning technological innovations with the demands of the energy transition.

From a strategic and political-scientific perspective, investigations conducted by Santos, Ottoni, and Nepomuceno (2022) and Koren et al. (2022) outline perspectives on the use of artificial intelligence as a resource that supports the global sustainable energy agenda. The authors survey the most frequent uses of AI across various renewable sources and emphasize the importance of interdisciplinarity among data science, electrical engineering, and public policy to enable a less carbon-dependent energy model. Similarly, the analysis by Cheng and Yu (2019), when examining the new generation of AI applied to smart energy, highlights the trend toward autonomous energy systems capable of self-management based on real-time information. The synergy among these methodologies facilitates the design of hybrid and resilient systems, in which artificial intelligence serves as a bridge connecting operational efficiency, environmental sustainability, and strategic decision-making.

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Table 1 — Artificial Intelligence Techniques Applied to the Integration of Renewable Energy Sources

Artificial Intelligence Technique	**Main Application**	**Associated Renewable Source**	**Reference**
Artificial Neural Networks	Forecasting solar irradiance and energy production	Solar	Aguiar-Furucho et al. (2024)
Fuzzy Logic	Handling imprecise environmental data	Solar	Garud, Jayaraj, and Lee (2021)
Genetic Algorithms	Optimization of hybrid system performance	Solar and Wind	Garud, Jayaraj, and Lee (2021)
Intelligent Robotics	Damage assessment in offshore wind turbines	Wind	Liu, Hajj, and Bao (2022)
Cyber-Physical Systems with AI	Real-time monitoring of power quality	Multiple	Kamio et al. (2024)
Hybrid Learning Models	Forecasting and response to climatic and operational variations	Solar and Wind	Cheng and Yu (2019); Santos et al. (2022)

Source: Garud et al. (2021), Liu et al. (2022), Kamio et al. (2024), Aguiar-Furucho et al. (2024), Cheng e Yu (2019), Santos et al. (2022) e Koren et al. (2022

The table synthesizes the main artificial intelligence techniques applied to renewable energy systems, highlighting their specific uses and corresponding sources. It was developed based on the studies of Garud et al. (2021), Liu et al. (2022), Kamio et al. (2024), Aguiar-Furucho et al. (2024), Cheng and Yu (2019), Santos et al. (2022), and Koren et al. (2022), facilitating the visualization of the most relevant technical-scientific approaches in the field of energy transition.

3.2 Decarbonization and Energy Efficiency

In 2015, the international community, through the United Nations, established the new Sustainable Development Goals (SDGs), known as the 2030 Agenda. SDG 7 (*Affordable and Clean Energy*) calls for, by 2030, the strengthening of international cooperation to facilitate access to research, including renewable energy, energy efficiency, and the promotion of investments in clean energy infrastructure and technologies (UN, 2015). Unsurprisingly, the energy transition has introduced a new paradigm for environmentally sustainable and economically viable energy sources and consumption patterns. At the core of this process, decarbonization emerges as a strategic axis that drives the restructuring of public policies, business models, and technological investments. Silva et al. (2025) propose a theoretical framework that links renewable energy to carbon neutrality, emphasizing the importance of systemic integration to ensure that decarbonization occurs in coordination with other economic dimensions, thus avoiding isolated or segmented interventions. The perspective of García-Sánchez et al. (2025) highlights the crucial role of institutional investors in transforming the business models of large multinational corporations, positioning climate governance as a fundamental component of corporate decision-making. The sustainable model based on open innovation, examined by Alvarez-Meaza, Pikatza-Gorrotxategi, and Rio-Belver (2020) in the case of Iberdrola, demonstrates that the adoption of sustainable practices not only reduces emissions but also ensures a long-term competitive advantage in the energy sector.

From the perspective of international policy, Ribeiro (2025) underscores Brazil's efforts to align its commitments with the demands of the global community, seeking both emission reductions and the promotion of renewable energy sources. Cooperation among nations, as emphasized by Gangotra, Dolan, and Carlsen (2024), is shown to be indispensable in addressing the challenges of industrial decarbonization, particularly in the face of fragmented unilateral initiatives. This view is supported by the European Environment Agency (2023), which points to the need for greater synergy between goals, regulations, and investments in sustainable infrastructure, stressing that, despite progress in several European countries, significant gaps remain to be addressed. Within these strategies, Direct Air Capture (DAC) and Direct Ocean Capture (DOC) technologies, as studied by Al Yafiee et al. (2024), present innovative methods for large-scale carbon removal, complementing existing mitigation plans, even in regions with high population density and intense industrial activity.

Table 2 — Key Strategies and Actors in the Decarbonization Process with a Focus on Energy Efficiency

Strategy or Action	Main Focus	Key Actors or Examples	Reference
Integration of renewable energy	Replacement of fossil-based energy matrices	Theoretical integration framework	Silva et al. (2025)
Corporate climate governance	Redefinition of business models	Institutional investors	García-Sánchez et al. (2025)
Open innovation with a sustainability focus	Value creation and emissions reduction	Iberdrola case study	Alvarez-Meaza et al. (2020)
International cooperation in industry	Integrated policies and joint action	Country-level integration proposals	Gangotra et al. (2024)
Monitoring of targets and indicators	Climate progress tracking	European Union	European Environment Agency (2023)
Direct carbon capture (DAC and DOC)	Large-scale CO_2 mitigation	Environmental capture technologies	Al Yafiee et al. (2024)
Intersection of economy and innovation	Pathways to carbon neutrality	Analysis of the Chinese scenario	Ahmad et al. (2024)
Diplomatic and regulatory positioning	Participation in international forums and treaties	Brazilian strategy	Ribeiro (2025)

Source: Silva et al. (2025), García-Sánchez et al. (2025), Alvarez-Meaza et al. (2020), Gangotra et al. (2024), European Environment Agency (2023), Al Yafiee et al. (2024), Ahmad et al. (2024) e Ribeiro (2025).

Table 2 synthesizes the main strategic pathways for decarbonization, linking concrete actions to relevant actors and initiatives. It was developed based on the contributions of Silva et al. (2025), García-Sánchez et al. (2025), Alvarez-Meaza et al. (2020), Gangotra et al. (2024), European Environment Agency (2023), Al Yafiee et al. (2024), Ahmad et al. (2024), and Ribeiro (2025), reflecting the multidimensional complexity of the energy transition.

From a technical standpoint, energy efficiency is an essential element in the relationship between decarbonization and the responsible use of energy. As pointed out by Ahmad, Raihan, and Ridwan (2024), the convergence of economic aspects, technological advances, and renewable energy sources demonstrates the potential to achieve carbon neutrality, provided it is supported by adequate incentive policies, smart infrastructure, and continuous innovation. Strengthening renewable energy sources must be accompanied by a responsible consumption mindset, considering that energy efficiency encompasses the entire cycle—from generation to distribution and reuse. Furthermore, measuring energy performance indicators, combined with the use of artificial intelligence–based technologies, can contribute to reducing losses, optimizing planning, and supporting strategic decision-making in both industrial and public sectors.

The correlation between decarbonization and energy efficiency is reinforced by the industrial integration of renewable energy sources, as emphasized by Silva et al. (2025), who suggest an integrated theoretical framework for systemic decarbonization. Increasing adoption of initiatives such as machinery upgrades, infrastructure digitalization, and the promotion of a circular economy by companies and governments is driving innovation and reducing costs in production and supply chains (Alvarez-Meaza et al., 2024). Thus, collaborative efforts and sustained investment in artificial intelligence technologies and carbon capture foster the development of resilient societies and economies, in alignment with global sustainability commitments.

3.3 Digital Competencies and Language Teaching: Preparing Brazil for the Future in MERCOSUR-EU Intelligent Integration of Renewable Sources in the Energy Transition

The effective coordination of diverse renewable sources within a transforming energy matrix requires addressing technical, economic, and regulatory challenges, as well as implementing digital technologies that enhance operational predictability and efficiency. Santos et al. (2025) discuss how the interconnection between sustainable energy, biodiversity, and the green economy can provide a foundation for a more equitable energy transition during periods of climate crisis. The integrated perspective is further emphasized by Lago and Aguiar (2018), who highlight the importance of electrical grids that are both more efficient and capable of adapting to the evolving demands of contemporary energy systems. The implementation of artificial intelligence in this context enables real-time data analysis, energy demand forecasting, and support for strategic decision-making. As López and Guaitolini (2022) note, smart energy grids constitute essential infrastructure for integrating variable sources, such as solar and wind, mitigating the effects of intermittency and increasing grid reliability.

The development of smart and sustainable cities creates a favorable context for the expansion of digitally managed, integrated energy systems. A report by EPE (2022) illustrates how urban initiatives focused on efficient energy use have played a significant role in advancing decentralized energy transition, particularly when combined with public policies and emerging technologies. Porto et al. (2020) introduce an expanded concept of human, intelligent, creative, and sustainable cities (CHICS), wherein energy consumption efficiency is closely linked to citizen engagement and social innovation. Within the context of urban mobility, Caciato and Mendes (2024) emphasize the importance of vehicle electrification as a transformative agent for both urban and energy systems, fostering a direct interconnection between sustainable transportation and adaptable energy grids. These urban dimensions broaden the scope of artificial intelligence applications, which increasingly operate in managing dynamic energy flows, real-time adaptation, and minimizing systemic losses.

Table 3 — Strategic Elements of the Intelligent Integration of Renewable Energy Sources in the Energy Transition

Strategic Element	Brief Description	Source
Smart Power Grids	Digital infrastructures for dynamic generation and demand management	López and Guaitolini (2022); Gallotti (2021)
Smart and Sustainable Cities (CHICS)	Urban environments integrating innovation, mobility, and efficiency	Porto et al. (2020); Caciato and Mendes (2024)
Urban Context Energy Planning	Local actions for energy efficiency and intelligent use	EPE (2022)
Ecosystemic Integration of Renewable Sources	Relationship between biodiversity, clean matrix, and green economy	Santos et al. (2025)
Sustainable Electric Systems	Infrastructure oriented towards efficiency and systemic adaptability	Lago and Aguiar (2018)
Artificial Intelligence Applied to the Transition	Tools for forecasting, decision-making, and energy transition management	Dias (2024)

Sources: Santos et al. (2025), Gallotti (2021), EPE (2022), Caciato and Mendes (2024), Dias (2024), Porto et al. (2020), Lago and Aguiar (2018), López and Guaitolini (2022).

Table 3 presents a synthesis of the main strategic elements supporting the intelligent integration of renewable sources, highlighting technical, urban, and environmental components. It was developed based on the works of Santos et al. (2025), López and Guaitolini (2022), Gallotti (2021), Porto et al. (2020), Caciato and Mendes (2024), Lago and Aguiar (2018), EPE (2022), and Dias (2024), offering an organized view of the multiple dimensions involved in the energy transition.

Intelligent integration also requires attention to regulatory obstacles and the equitable distribution of generated benefits. Gallotti (2021) notes that the advancement of smart grids still faces normative limitations that constrain the expansion of these infrastructures in certain regional contexts. In this setting, the role of artificial intelligence encompasses maximizing the use of available energy resources while also contributing to the modeling of regulatory scenarios that facilitate the incorporation of diverse renewable sources. Dias (2024), when discussing the opportunities and challenges of renewable energy for achieving the Sustainable Development Goals, emphasizes that technological adoption must be preceded by governance mechanisms capable of ensuring that progress unfolds in a coordinated manner and produces positive effects for local communities. Integrated collaboration between public and private actors, facilitated by advanced technologies, presents viable alternatives for restructuring the energy matrix from a sustainability perspective.

IV. DISCUSSION AND CONCLUSION

The present research fully achieved its established objectives, both in general terms and in specific aspects. The primary aim—assessing the contribution of artificial intelligence to the effective integration of renewable sources in energy transition contexts—was accomplished through a qualitative approach structured around three analytical axes. The investigation of the main applications of artificial intelligence in energy system management revealed a variety of techniques employed for forecasting, optimization, and monitoring, as illustrated in **Table 1**. Moreover, the study clearly identified the consequences of decarbonization for energy efficiency and emission reduction, as reflected in the strategies and actions presented in **Table 2**. Finally, the challenges and opportunities associated with the intelligent integration of sustainable technologies were addressed, as summarized in **Table 3**, highlighting the importance of digital solutions and systemic structures in promoting a sustainability-oriented energy transition.

The data presented in the qualitative tables provide a comprehensive and interconnected perspective on contemporary contributions of artificial intelligence across various areas of the global energy agenda. **Table 1** organized techniques such as neural networks, fuzzy logic, genetic algorithms, and hybrid models, linking each to specific sources and significant applications in solar, wind, or hybrid energy systems. **Table 2** emphasized decarbonization strategies being implemented across institutional spheres, highlighting the roles of governments, international organizations, investors, and private-sector actors in formulating integrated policies. In **Table 3**, the evaluation of strategic components underscored the relevance of smart infrastructures, urban governance, and the connection between biodiversity and a clean energy matrix. The interrelation of these tables allowed for an integrated understanding of how technological resources and policy choices are interconnected in the design of more resilient and efficient energy systems.

In conclusion, the findings corroborate that the implementation of artificial intelligence methodologies is closely associated with the enhancement of energy management, fostering greater predictability, operational efficiency, and adaptability to climate variability and demand conditions. The joint examination of the three tables demonstrated that technological advances, when combined with consistent institutional policies and clearly defined territorial strategies, promote the development of more resilient energy models aligned with the objectives of the global energy transition. The intersection of technical, environmental, and political factors revealed that the incorporation of renewable sources requires not only sophisticated computational solutions but also institutional harmonization that enables sustainable innovations in the production, distribution, and consumption of energy over the medium and long term.

As a continuation of the current analysis, it is recommended to conduct empirical studies evaluating artificial intelligence–based models applied to regional renewable energy initiatives. Future research could also examine comparisons across different geographic contexts to assess the feasibility of the examined solutions in diverse socioeconomic realities. Additionally, it will be important to analyze how regulatory, cultural, and institutional factors impact technological integration in sustainable energy systems, particularly in developing countries. These pathways indicate the ongoing relevance of a scientific agenda dedicated to an energy transition that is just, sustainable, and technically viable.

REFERENCES

[1] Aguiar-Furucho, M. A., Gurski, E., Furucho, R. A., & Benedito, R. A. de S. (2024). Artificial neural networks in solar irradiance forecasting: A case study with a problem-based approach for renewable energy education. *Caderno Pedagógico, 21*(10), e8536. https://doi.org/10.54033/cadpedv21n10-002

[2] Ahmad, S., Raihan, A., & Ridwan, M. (2024). Role of economy, technology, and renewable energy toward carbon neutrality in China. *Journal of Economy and Technology, 2*, 138–154. https://doi.org/10.1016/j.ject.2024.04.008

[3] Al Yafiee, O., et al. (2024). Direct air capture (DAC) vs. direct ocean capture (DOC): A perspective on scale-up demonstrations and environmental relevance to sustain decarbonization. *Chemical Engineering Journal*, 154421. https://doi.org/10.1016/j.cej.2024.154421

[4] Alvarez-Meaza, I., Pikatza-Gorrotxategi, N., & Rio-Belver, R. M. (2020). Sustainable business model based on open innovation: Case study of Iberdrola. *Sustainability, 12*(24), 10645. https://doi.org/10.3390/su122410645

[5] Bandeira, H. M. M. (2022). How to elaborate a data analysis plan in qualitative research: Description, explanation, or interpretation? *Educação e Filosofia, 36*(77). https://doi.org/10.14393/revedfil.v36n77a2022-65312

[6] Caciato, L. E., & Mendes, L. de S. (2024). Smart cities: Energy transition for electric vehicles in the construction of green cities. *Periódico Técnico Científico Cidades Verdes, 12*(35). ISSN: 2317-8604

[7] Cavalcante, L. T. C., & Oliveira, A. A. S. de. (2020). Methods of bibliographic review in scientific studies. *Psicol. Rev. (Belo Horizonte), 26*(1), 82–100. https://doi.org/10.5752/P.1678-9563.2020v26n1p82-100

[8] Cheng, L., & Yu, T. (2019). A new generation of AI: A review and perspective on machine learning technologies applied to smart energy and electric power systems. *International Journal of Energy Research, 43*(6), 1928–1973.

[9] Dias, R. (2024). The role of renewable energy in achieving the SDGs: Opportunities and challenges. *Recima21 – Multidisciplinary Scientific Journal, 5*(1), e514845. ISSN: 2675-6218. https://doi.org/10.47820/recima21.v5i1.4845

[10] EPE – Empresa de Pesquisa Energética. (2022). Initiatives in cities for intelligent energy use: The role of cities in energy management [Technical Report]. Brasília: EPE. https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-519/topico-626/IT2%20-%20Iniciativas%20na%20cidades%20para%20o%20uso%20inteligente%20da%20energia.pdf

[11] European Environment Agency (EEA). (2023). *Trends and projections in Europe 2023: Tracking progress towards Europe's climate and energy targets.* EEA.

[12] Gallotti, V. D. M. (2021). Smart electrical grids. *Research, Society and Development, 10*(9), e30010918322. ISSN: 2525-3409. http://dx.doi.org/10.33448/rsd-v10i9.18322

[13] Gangotra, A., Dolan, A., & Carlsen, W. (2024, November 23). WRI Brazil: To decarbonize the industrial sector, countries must go beyond individual action. https://www.wribrasil.org.br/noticias/descarbonizar-setor-industrial-cooperacao-paises-internacional

[14] García-Sánchez, I.-M., et al. (2025). Decarbonisation strategies and climate governance: Are institutional investors reshaping the business model of multinationals? *Journal of Innovation & Knowledge, 10*(3), 100698.

[15] Garud, K. S., Jayaraj, S., & Lee, M. Y. (2021). A review on modeling of solar photovoltaic systems using artificial neural networks, fuzzy logic, genetic algorithm, and hybrid models. *International Journal of Energy Research, 45*(1), 6–35.

[16] Kamio, E., Guimarães, G. E., Leite, J. C., Almeida, A. A. S. de, Monteiro, O. B., Ribeiro, P. F. da S., & Nascimento Filho, A. G. do. (2024). Computational architecture for energy quality monitoring control using artificial intelligence tools focused on Industry 4.0 with integration of renewable energies. *Revista de Gestão e Secretariado, 15*(12), e4494. https://doi.org/10.7769/gesec.v15i12.4494

[17] Koren, B. B., Yamamoto, A. T. M., Bonacina, A. L. F., & Pinheiro, L. (2022, December 19–21). Artificial intelligence (AI) and renewable energy: A 2030 research agenda. In *19th CONTECSI – International Conference on Information Systems and Technology Management*. TECSI – FEA USP, São Paulo, Brazil. ISSN: 2448-1041. https://doi.org/10.5748/19CONTECSI/PSE/SOC/7026

[18] Lago, R. L. V. B., & Aguiar, A. de O. E. (2018). Efficient, intelligent, and sustainable electrical systems: Realities and perspectives. In *XX ENGEMA – International Meeting on Business Management and Environment*. ISSN: 2359-1048

[19] Liu, Y., Hajj, M., & Bao, Y. (2022). Review of robot-based damage assessment for offshore wind turbines. *Renewable and Sustainable Energy Reviews, 158*, 112187.

[20] López, M. N., & Guaitolini, S. (2022). Smart energy grids. *Revista Esfera Acadêmica Tecnologia, 7*(2). ISSN: 2526-4141

[21] Porto, A. G., Frees, C., Doria, F., & Campolargo, M. (2020). The future belongs to CHICS: How to build human, intelligent, creative, and sustainable cities. 1st Edition. Brazilian Institute of Intelligent, Human, and Sustainable Cities. ISBN: 978-65-87770-00-0

[22] Ribeiro, J. P. M. (2025). Brazil, international communities, and the pursuit of decarbonization. *Research, Society and Development, 14*(6), e3214648945. ISSN: 2525-3409. http://dx.doi.org/10.33448/rsd-v14i6.48945

[23] Santos, A. N. S., et al. (2025). Energy transition and preservation: Integration of renewable sources, biodiversity, and green economy in times of climate crisis. *Revista Observatorio de la Economia Latinoamericana, 23*(3), 1–37. ISSN: 1696-8352. https://doi.org/10.55905/oelv23n3-041

[24] Santos, S. O. S., Ottoni, A. L. C., & Nepomuceno, E. G. (2022). Applications of artificial intelligence in renewable energy: A systematic review. In *Sociedade Brasileira de Automática (SBA) XXIV Congresso Brasileiro de Automática – CBA 2022*, October 16–19, 2022. ISSN: 2525-8311. https://doi.org/10.20906/CBA2022/3530

[25] Silva, E. V. da, Santos, G. P. R. dos, Feliz, R. G., Feliz, A. C. de M., Corrêa, A. de C., Imbiriba, K. G., Carr, R. F., Souza, R. B. R. A., Santos, F. M. T. dos, Reis, W. A. dos, Nascimento, G. da S., & Ferreira Filho, H. R. (2025). Carbon neutrality and renewable energy: An integrated theoretical framework for systemic decarbonization of the global economy. *Caderno Pedagógico, 22*(7), e16041. https://doi.org/10.54033/cadpedv22n7-037

[26] Simões, R., de Moura, J. M. B. M., & da Silva, A. C. (2023). Documentary research: A technique for identifying problems in the capture of federal resources in the basic sanitation sector. *Revista de Gestão e Secretariado, 14*(6), 9196–9218. https://doi.org/10.7769/gesec.v14i6.2289