IOSR Journal of Business and Management (IOSR-JBM)
e-ISSN:2278-487X, p-ISSN: 2319-7668. Volume 27, Issue 6. Ser. 13 (June 2025), PP 37-47
www.iosrjournals.org

Curtailment, Sustainability, and Governance: The Strategic Role of Renewable Energy Sources within the ESG Framework

Spec. André Luiz Barros de Oliveira[1] https://orcid.org/0000-0002-2838-4208; B. Sc. (Cand.) Ana Katherine Silveira Pereira Caracas[2] https://orcid.org/0009-0003-9374-9175; M. Sc. (Stud.) Antonio Werbiton Marinho Almeida[3] https://orcid.org/0009-0002-1904-7522; Spec. Erica Cristina Machado de Melo[4] https://orcid.org/0009-0000-3273-2124; M. Sc. Francisco Ademir Eduardo Freitas[5] https://orcid.org/0009-0009-3230-6593; PhD. Francisco José Lopes Cajado[6] https://orcid.org/0000-0002-8824-9251; Dr. Givanildo Ximenes Santana[7] https://orcid.org/0000-0001-8337-1082; Spec. Irene Mendes Fontes[8] https://orcid.org/0009-0002-3152-6649; Profa. Spec. Isabela Maciel Taveira[9] Https://Orcid.Org/0009-0004-0666-3662; Spec. Lizandra Régia Miranda da Silva[10] https://orcid.org/0009-0007-4287-6157; Profa. Dra. Luisa Janaina Lopes Barroso Pinto[11] https://orcid.org/0000-0003-1505-5461; M. Sc. Márcio Carneiro Barbosa[12] https://orcid.org/0009-0003-8290-1127; Ph.D. Paulo Henrique Barbosa Sousa[13] https://orcid.org/0009-0007-1269-7860; Rickardo Léo Ramos Gomes[14] https://orcid.org/0000-0001-6101-9571; Ph. D. Student Roberto Augusto Caracas Neto[15] https://orcid.org/0000-0001-8484-411X.

[1](Postgraduate in MBA in Renewable Energy Management (IEL/FBUNI)), [2](Undergraduate Student in Chemical Engineering), [3](Master's student in Administration and Controllership at UFC), [4](Postgraduate Degree in Strategic People Management from FBUNI University Center), [5](Professional Master's in Climatology and Applications in CPLP Countries and Africa – UECE), [6](Ph.D. in Agricultural Biotechnology (RENORBIO – UFC), [7](Ph.D. in Genetics, Conservation, and Evolutionary Biology National Institute of Amazonian Research, Manaus-AM, Brazil), [8](Postgraduate Degree in Criminal Law from Uniateneu University Center), [9](Specialist in Wind Energy – CTGás), [10](Postgraduate in MBA in Renewable Energy Management (IEL/FBUNI), [11](Ph.D. in Development and Environment – Federal University of Ceará (UFC), [12](M. Sc. in Military Sciences – Army Command and General Staff School), [13](Ph.D. in Educational Sciences, FCSA (DINTER Program), [14](Doctorate in Biological Sciences - FICL; Master's in Phytotechnics - Federal University of Ceará), [15](Doctoral Student at the Academy of the National Institute of Industrial Property)
Corresponding Author: Rickardo Léo Ramos Gomes

Abstract:
Background: *The global expansion of renewable energy sources in the electricity matrix has intensified the challenges related to curtailment, which refers to the restriction of energy production due to technical, regulatory, or economic factors. Although rarely addressed explicitly, this phenomenon has direct consequences for the sustainability and efficiency of power systems, requiring new governance strategies aligned with Environmental, Social, and Governance (ESG) principles. In this context, the study investigates the strategic role of renewable energy in promoting more sustainable and resilient curtailment management, emphasizing its relevance to the energy transition and the development of management models suited to current climate challenges.*
Materials and Methods: *This research employed a qualitative methodology based on epistemological principles that value the analysis of social phenomena within their specific historical and institutional contexts. It is classified as a theoretical-analytical study, grounded in a review of international scientific and technical literature, and focused on the intersection of curtailment, energy sustainability, and governance within the ESG framework.*
Results: *The main objective of the study was to analyze the relationship between renewable energy curtailment and ESG principles, while proposing scientifically grounded and strategic guidelines for sustainable curtailment*

management in the energy sector. The research identified regulatory, technical, and institutional gaps and, by suggesting integrative guidelines based on analytical and theoretical evidence, it provides significant contributions to the development of public policies and corporate strategies that are more efficient, transparent, and environmentally responsible.
Conclusion: *The consolidation of specific metrics, the promotion of technological innovation, and the articulation between public and private actors emerge as viable strategies to transform curtailment-related challenges into opportunities, ensuring that the growth of renewable energy sources is accompanied by efficient and sustainable management. Thus, addressing curtailment goes beyond operational concerns, becoming a key element of the global agenda for a fair, efficient, and environmentally consistent energy transition in the 21st century.*

Keywords: *Curtailment; ESG; Renewable Energy; Energy Transition.*

Date of Submission: 12-06-2025 Date of Acceptance: 25-06-2025

I. Introduction

The expansion of renewable energy sources is widely regarded as a cornerstone of the energy transition and a key strategy for addressing climate change. However, this progress faces technical and structural challenges that hinder its full effectiveness, among which the phenomenon of curtailment stands out—a term referring to the intentional restriction of energy production, even when renewable sources are fully available. While this procedure is necessary in certain operational contexts, it reveals significant contradictions in the path toward sustainability, particularly by undermining the optimal use of clean resources and the economic viability of renewable energy projects. In this context, the need to incorporate curtailment into discussions surrounding ESG (Environmental, Social, and Governance) criteria becomes increasingly evident. These criteria are emerging as strategic benchmarks for organizations and institutions committed to sustainable, transparent, and socially responsible practices.

In response to this issue, the present study adopts a qualitative, theoretical-analytical approach grounded in a systematic review of scientific and documentary literature from the past five years. This includes reports from international institutions such as the IEA and IRENA, as well as specialized publications on ESG. The methodology involves critical and comparative analysis of secondary data, along with the construction of tables and graphs to synthesize the most relevant findings. This strategy aims not only to outline the current state of knowledge regarding curtailment and its implications but also to suggest practical guidelines for its mitigation within the scope of ESG-related requirements.

The overarching objective of this study is to analyze the relationship between the curtailment of renewable energy and ESG principles, proposing scientific and strategic guidelines for the sustainable management of curtailment in the energy sector. More specifically, the study aims to: (a) investigate the main causes and impacts of curtailment in renewable energy systems; (b) assess the role of ESG metrics in the management and mitigation of curtailment; and (c) propose strategic guidelines and solutions to integrate curtailment control into corporate environmental governance practices.

To achieve these objectives, the article is structured into five interrelated sections. Following this introduction, the Materials and Methods section outlines the methodological principles of the research. The Theoretical Framework is then organized into three subsections addressing the causes and effects of curtailment, its connection to ESG practices, and strategies for its reduction. The Discussion section presents a critical analysis of the results and offers guidelines for the sustainable management of the phenomenon. Finally, the Conclusion summarizes the study's key contributions and highlights avenues for future research.

II. Material And Methods

This study employed a qualitative methodology grounded in epistemological principles that value the analysis of social phenomena within their specific historical and institutional contexts (Guerra et al., 2024). The investigation is classified as theoretical-analytical, based on a review of international scientific and technical literature, focusing on the intersection of energy curtailment, energy sustainability, and governance within the framework of ESG (Environmental, Social, and Governance) guidelines.

The research was structured around two complementary methodological pillars: a systematic literature review and document analysis. The systematic review encompassed the selection and examination of publications from the past five years, with an emphasis on indexed journal articles, reports from international energy agencies, and specialized investigations on ESG. This process followed the protocols outlined by Bandeira et al. (2021), employing explicit inclusion criteria such as thematic relevance, methodological rigor, and the impact factor of the sources. The databases consulted included Scopus, Web of Science, and ScienceDirect, in addition to institutional repositories associated with the IEA (International Energy Agency), IRENA (International Renewable Energy Agency), and ANEEL (Brazilian Electricity Regulatory Agency).

In addition, a document analysis was conducted following the methodological guidelines proposed by Lima Junior et al. (2021), with a focus on technical-scientific and regulatory documents, including annual reports, operational manuals, and institutional publications from the aforementioned agencies. Documents were selected based on their recency, institutional representativeness, and relevance to understanding curtailment mitigation strategies within the energy transition landscape.

The data collected were organized into analytical tables and graphs, developed according to the principles of statistical literacy (Gould, 2017), allowing for the comparison of key findings. The evidence was critically examined using inductively constructed thematic categories, based on patterns and recurrences identified in the texts. This analysis also incorporated the triangulation of secondary sources and case studies cited in the reviewed documents, following the methodology suggested by Ribeiro (2021), thereby ensuring robustness and depth in the interpretation of the information.

This methodological approach proved essential for achieving the objectives of the study, providing a solid foundation for the critical analysis of the relationship between renewable energy curtailment and the principles of Environmental, Social, and Corporate Governance (ESG). The integration of the systematic review and document analysis enabled the identification of the most significant causes and impacts of curtailment, as well as the evaluation of the role of ESG metrics in its management and mitigation. The combination of qualitative analysis techniques with the principles of statistical literacy and the triangulation of sources allowed the study to ensure the consistency and analytical depth necessary to formulate scientific guidelines and governance strategies capable of informing sustainable practices in the energy sector. Thus, the methods implemented not only enabled the identification of patterns, trends, and gaps, but also substantiated the proposal of viable solutions for integrating curtailment control with corporate environmental governance practices.

III. Literature Review

The theoretical framework of this study aims to provide an integrated and in-depth understanding of the relationship between renewable energy curtailment and ESG (Environmental, Social, and Governance) guidelines, addressing technical, environmental, and governance aspects. To this end, the theoretical exposition is organized into three central subsections.

The first section, Curtailment in Renewable Energy: Causes, Impacts, and Trends (3.1), analyzes the structural and operational factors that lead to the restriction of renewable energy generation, as well as examining its economic and environmental repercussions, based on recent research and forecasts.

The second subsection, The Incorporation of Curtailment in ESG Practices: Current Diagnosis (3.2), investigates how the issue of curtailment has been integrated—or overlooked—in the ESG strategies and reporting of companies and organizations within the energy sector.

Finally, the third subsection, Strategic Guidelines for the Reduction of Curtailment Integrated with ESG (3.3), proposes viable and sustainable approaches for mitigating curtailment, linking these strategies to current demands for sustainability, social responsibility, and corporate governance. This structure is designed to provide a robust theoretical foundation to support the analyses and recommendations developed throughout the article.

Curtailment in Renewable Energy: Causes, Impacts, and Trends

Curtailment, or constrained-off, in renewable energy systems represents an increasingly significant challenge for the sustainability and operational efficiency of modern electrical grids. According to the IEA (2023), the substantial rise in the integration of intermittent renewable sources, such as solar and wind, creates a need to balance supply and demand in real time, which often results in the intentional reduction of generation (curtailment) to prevent grid instabilities and overloads. This phenomenon is driven by various factors, including infrastructure limitations, transmission constraints, and the lack of flexibility in existing systems (Nycander et al., 2020; O'Shaughnessy, Cruce & Xu, 2021).

Table 1 – Main Causes of Curtailment in Renewable Energies

Cause	**Description**
Grid limitation	Insufficient capacity of the transmission or distribution network.
Excess generation	Energy production exceeds local demand.

Cause	**Description**
Climatic factors	Sudden variations in wind or solar radiation requiring curtailment.
Scheduled maintenance	Shutdown of lines or equipment for maintenance.

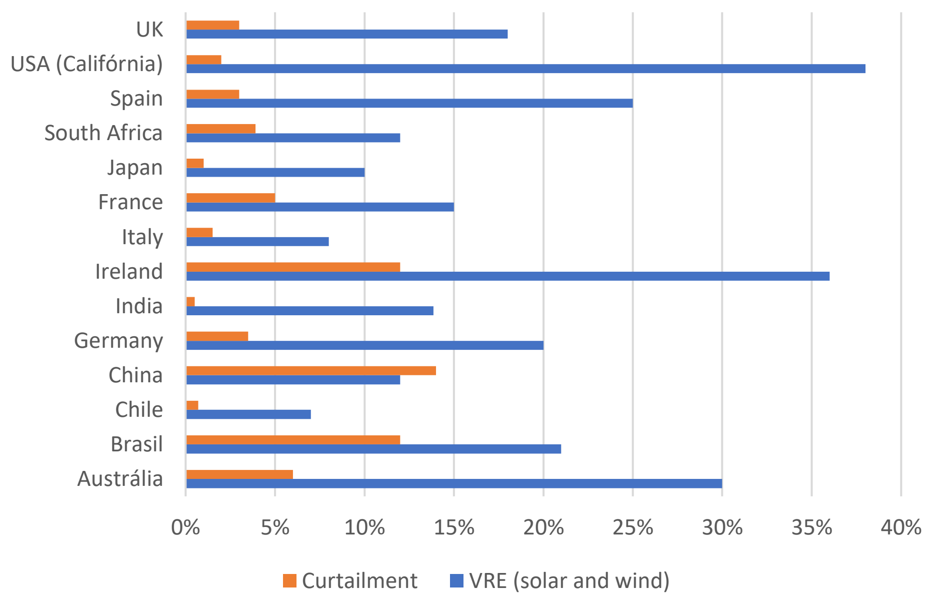
Note. Adapted from Nycander, E., Soder, J., Olauson, J., & Eriksson, R. (2020); O'Shaughnessy, E., Cruce, J., & Xu, K. (2021); and Correia, T. de B. C. (2020).

Table 1 synthesizes the main causes of curtailment in renewable energy systems, grouping them into four categories: grid limitation, overgeneration, climatic factors, and scheduled maintenance. These causes reflect the operational and structural challenges faced by electrical systems in integrating intermittent sources such as solar and wind energy. According to Nycander et al. (2020), the limited capacity of transmission and distribution networks constitutes one of the primary bottlenecks hindering the full utilization of generated energy. O'Shaughnessy, Cruce, and Xu (2021) further emphasize that overgeneration—particularly during periods of low demand—significantly contributes to curtailment, highlighting the urgent need for investments in energy storage and grid flexibility. Correia (2020) notes that although climatic conditions and scheduled outages are predictable, they demand strategic operational planning to mitigate losses and ensure system reliability. Thus, the table underscores that mitigating curtailment requires integrated technical, regulatory, and operational solutions.

The International Energy Agency (IEA) has observed that curtailment of renewable electricity generation approaches 10% in several countries, leading to the transfer of restriction-related costs to consumers. Consequently, the societal benefits of low-cost electricity are delayed. Accelerating the delivery of these benefits is a political, economic, and social imperative. Hence, the importance of expanding the grid using modern technologies that enhance its flexibility and accessibility (IPCC, 2012).

Figure 1 below illustrates the contribution of variable renewable energy sources (VRE), predominantly solar and wind, to the total electricity generation mix, alongside the technical curtailment rates for different countries. It is noteworthy that nations with higher penetration of VRE—such as the United States (California), Ireland, and Australia—also exhibit relatively high curtailment rates, highlighting the challenges associated with integrating these intermittent sources into the power grid. This trend corroborates studies such as those by Nycander et al. (2020) and O'Shaughnessy, Cruce, and Xu (2021), which underscore the need for increased grid flexibility and technological innovation to reduce energy losses and preserve system stability.

Figure 1 - VRE shares in generation and technical curtailment for selected countries



Source: IEA (2023)

According to Schierenbeck (2025), grid flexibility would directly translate into lower energy costs for consumers. By optimizing the use of existing infrastructure and reducing curtailment, modern grids could stabilize electricity prices.

Moreover, countries with moderate or low VRE penetration, such as Japan and Chile, exhibit significantly lower curtailment rates, reflecting the influence of regional grid characteristics and regulatory policies in curtailment management. This diversity among countries demonstrates that the phenomenon is not homogeneous and is subject to multiple factors, such as infrastructure, storage capacity, and regulatory frameworks, as argued by Correia (2020) and Joskow (2019). Hence, the evaluation of the graph underscores the importance of context-specific strategies in the transition to sustainable energy.

In situations of overgeneration or inertia-induced scarcity, system operators often resort to VRE curtailment as a mitigation measure—meaning the reduction of output from VRE units by a system operator to address flexibility challenges. In wind turbines, this can be achieved by pitching the blades out of the wind; in photovoltaic solar technologies, production can be curtailed through smart inverters or by simply disconnecting certain units (IRENA, 2018).

The consequences of curtailment extend beyond mere energy loss, directly impacting the economic viability of renewable energy projects and the sustainability image associated with such investments. Joskow (2019) emphasizes that curtailment can discourage further investment in renewable energy, thereby undermining global decarbonization goals and ESG (Environmental, Social, and Governance) commitments. Furthermore, Nycander et al. (2020) highlight that limited transmission capacity, coupled with insufficient system flexibility, plays a significant role in increasing curtailment, underscoring the urgency of integrated strategies for the effective management of distributed generation.

Rolim (2025) states that there are at least ten justifications for curtailment—and, consequently, the necessity for compensation to affected producers—including constraints in grid capacity, oversupply during specific periods, lack of energy storage systems, and insufficient market signaling. These elements point to a disconnect between the planning of renewable energy expansion and the upgrading of transmission infrastructure, resulting in economic losses and disincentivizing continued investment in the sector.

Beyond technical aspects, the effects of curtailment have direct repercussions on the sustainability of the energy sector and its strategic role within ESG practices. As Rolim (2025) highlights, the interruption of renewable energy generation not only impairs the efficiency of power systems but also weakens the climate commitment of institutions and governments aiming for energy transitions based on clean sources. Therefore, understanding the structural and operational causes of curtailment is essential to proposing strategies that integrate renewable energy expansion, supply reliability, and economic equity for producers. Identifying these causes and their effects enables progress in developing public policies, regulatory instruments, and market mechanisms that ensure the full and sustainable integration of renewable energy in alignment with responsible energy governance principles.

Recent studies indicate that advancements in technological and regulatory solutions are crucial for mitigating the effects of curtailment. Correia (2020) underscores the relevance of regulatory policies that promote grid adaptability, energy storage, and infrastructure modernization. Troncoso (2025), in turn, presents lessons drawn from global experiences that transform challenges into opportunities, highlighting models that integrate smart storage and compensation systems for affected producers. According to Almeida (2025), this perspective is further enriched by addressing the effects of curtailment in the energy transition, indicating that the harmonization between governance and technological innovation is fundamental to ensuring the sector's sustainability.

Thus, analyzing the causes and effects of curtailment not only contributes to the improvement of energy policies but also reinforces the strategic importance of renewable energy within the ESG framework, facilitating a more robust and effective energy transition.

The Integration of Curtailment into ESG Practices: Current Diagnosis

The integration of ESG (Environmental, Social, and Governance) principles into corporate strategies has increasingly emerged as a response to growing demands for socio-environmental responsibility and transparency in governance procedures. Within the scope of renewable energy, this approach becomes particularly significant, considering projections that these sources will play a pivotal role in the transition to a sustainable energy matrix. The rising trend toward the adoption of green products (with lower environmental impact) that yield social benefits has compelled companies to embrace ESG-oriented policies (Bezerra, 2023).

However, the occurrence of curtailment — or the forced reduction of renewable energy generation — directly affects environmental and governance indicators, underscoring the urgency of a critical assessment of how it is managed within the framework of ESG metrics. Nunes et al. (2024) emphasize that corporate sustainability is tied not only to the implementation of renewable sources, but also to the ability to effectively integrate them into the power system, thereby preventing operational losses and misalignments with established climate commitments.

Curtailment, by limiting the full utilization of renewable energy sources, produces detrimental effects on environmental indicators by preventing the use of available clean energy. In some cases, this leads to the activation of conventional, more polluting energy sources. Rolim (2025) highlights that reductions in renewable energy generation often stem from technical, regulatory, or structural constraints, which necessitate compensatory mechanisms for affected producers and reveal weaknesses in sectoral management.

In this scenario, the challenges faced by companies extend beyond renewable energy generation and encompass its effective and continuous integration into the grid. Murasawa (2022) points out that the credibility of environmental targets is intrinsically linked to how effectively organizations address structural barriers such as curtailment, which can compromise a company's reputation in the eyes of investors and regulators who monitor the coherence between sustainability discourse and actual practice.

The implementation of ESG guidelines by energy sector organizations requires the use of regulatory instruments and performance indicators that enable monitoring and transparency in environmental and governance-related actions.

According to Assunção (2021) and Guevara and Dib (2022), the consolidation of the ESG agenda within institutions is directly associated with the capacity to measure impacts, risks, and opportunities related to climate change and energy efficiency. In this context, the adoption of internationally recognized frameworks has proven essential for ensuring compliance with sustainability standards, particularly in situations where curtailment may hinder decarbonization goals. Table 2 below presents three of the main ESG frameworks that address energy efficiency issues and are widely adopted by companies operating in the renewable energy sector:

Table 2 – ESG Frameworks Addressing Energy Efficiency

Framework	**Relevant Features**
GRI (Global Reporting Initiative)	Energy and emissions indicators.
SASB (Sustainability Accounting Standards Board)	Specific metrics for renewable energy.
TCFD (Task Force on Climate-related Financial Disclosures)	Analysis of climate-related risks and opportunities.

Sources: Assunção (2021); Guevara e Dib (2022); Machado e Checon (2023); Gomes et al. (2024)

The demands of the financial market and regulatory bodies have increasingly pressured corporations not only to disclose their environmental and governance practices, but also to demonstrate tangible outcomes. Gomes et al. (2024) highlight that corporate education focused on fostering an ESG-oriented culture is essential for strengthening organizational citizenship and sustainability, encompassing the efficient management of resources and the mitigation of operational risks such as curtailment. The implementation of effective ESG metrics can thus serve as a strategic tool for identifying weaknesses within the energy system, while also proposing solutions that enhance reliability and predictability in renewable energy operations. Vieira (2022), in turn, emphasizes that energy efficiency can only be achieved through the elimination of barriers — such as generation constraints — that limit decarbonization potential and compromise the achievement of carbon neutrality targets.

The application of ESG criteria in the energy sector plays a vital role in curtailment reduction, promoting greater operational efficiency, technological advancement, and social acceptance of energy infrastructure. The interconnection between corporate governance, environmental responsibility, and social engagement forms a robust foundation for addressing the challenges arising from unforeseen energy losses. Table 3 below illustrates how each of the ESG components can directly contribute to the reduction of curtailment:

Table 3 – Correlation between ESG Adoption and Curtailment Reduction

ESG Factor	**Contribution to Curtailment Reduction**
Governance	Improved management of energy assets and infrastructure.
Environmental	Promotion of storage technologies and smart grids.
Social	Encouragement of social acceptance of energy infrastructure.

Souces: Assunção (2021); Guevara e Dib (2022)

Moreover, curtailment directly challenges the principles of sound corporate governance. According to Machado and Checon (2023), companies that position themselves as committed to ESG must demonstrate alignment between their actions and the established governance standards, which includes transparency in managing the technical and economic risks associated with renewable energy production.

An inadequate approach to curtailment may be perceived as negligence or a lack of strategic preparedness, ultimately affecting investor perception and undermining the organization's market appeal. Assunção (2021) argues that the private sector must establish robust voluntary commitments to mitigate the effects of curtailment, integrating this issue into the core of corporate strategies aimed at achieving net-zero emission targets.

An effective ESG approach must, therefore, consider curtailment as a critical variable to be proactively managed. The interconnection between public policy, infrastructure investment, and technological advancement is fundamental to overcoming this challenge. Guevara and Dib (2022) emphasize that the opportunities linked to ESG principles are contingent upon the ability of organizations to respond to external pressures through effective and sustainable actions.

In this regard, Rolim (2025) contends that, due to the complexity of curtailment's underlying causes, it is essential to develop regulatory mechanisms that not only ensure compensation for producers but also promote grid modernization and the implementation of energy storage technologies.

Building a robust energy governance structure—grounded in clearly defined environmental, social, and governance (ESG) indicators—will be essential to ensure that the expansion of renewable energy sources translates into meaningful sustainability gains, mitigates the distortions caused by curtailment, and strengthens the climate commitments of both nations and corporations.

Strategic Guidelines for Curtailment Reduction Integrated into ESG

The increasing share of renewable sources in Brazil's energy matrix has intensified discussions on curtailment and its implications for the sector's sustainability. This phenomenon—characterized by limitations on energy generation despite the availability of natural resources—exposes structural and operational weaknesses in the integration of intermittent sources, such as wind and solar energy, into the power grid. As noted by Valente, Sobrosa, and Terra (2024), this situation is particularly prevalent in Brazil's Northeast region, which hosts a significant concentration of wind farms. However, transmission infrastructure constraints hinder the full dispatch of the energy produced.

In this context, the development of strategic guidelines that combine technical and governance solutions, aligned with ESG principles, is essential for minimizing energy losses, enhancing energy security, and enabling a more equitable and efficient energy transition. Among the most promising technical options for reducing curtailment is energy storage.

According to Castro et al. (2022), technologies such as battery systems and green hydrogen production enhance the operational flexibility of the grid by enabling the absorption of excess energy generated during periods of low demand, thereby contributing to grid stability. These solutions are further supported by smart grid technologies and demand-side management strategies, which optimize the utilization of generated energy. According to the Regulatory Impact Report by ANEEL (2020), the integration of hybrid power plants into smart grids enhances the resilience of Brazil's national interconnected system.

Research conducted by Pontes (2024) and Pinho (2017) underscores the technical and economic feasibility of producing hydrogen from wind energy surpluses, particularly in the Northeast, while also presenting viable alternatives for the efficient use of otherwise curtailed energy. Table 4 outlines a set of strategic guidelines for curtailment reduction, categorized by type of action:

Table 4 – Strategic Guidelines for Curtailment Reduction

Guideline	**Description**
Energy storage	Use batteries to absorb surplus energy.
Demand flexibility	Manage consumption dynamically.

Guideline	**Description**
Grid expansion	Invest in infrastructure to avoid bottlenecks.

Sources: ANEEL (2020); Castro et al. (2022); Luz e Vila (2024); Valente, Sobrosa e Terra (2024)

These approaches are supported by both Brazilian and international experiences, although their implementation requires financial investments in innovation and regulatory adjustments. In the Brazilian context, battery storage and the use of green hydrogen have already been explored through pilot projects; however, they still face challenges related to cost and regulatory frameworks. Demand-side management, in turn, calls for greater digitalization of electricity networks and increased consumer engagement, while grid expansion depends on strong public policies and long-term integrated planning.

On the international front, initiatives such as the implementation of wake steering in wind turbines in the United States, as reported by Seiler and Hoyt (2020), demonstrate the effectiveness of dynamic control strategies in optimizing production under curtailment conditions. This technique modifies wind flow paths between turbines and requires complex predictive models as well as advanced infrastructure, raising questions about its feasibility in Brazil given current technological and regulatory limitations. Nonetheless, Luz and Vila (2024) emphasize that energy planning based on hourly annual simulations that account for climatic variability and different demand scenarios is essential for making more resilient decisions.

From a governance standpoint, incorporating curtailment monitoring into Environmental, Social, and Governance (ESG) reporting represents a strategic advancement. Troncoso (2025) advocates for the implementation of specialized metrics to address this phenomenon, fostering greater transparency regarding operational losses and the mitigation strategies employed by energy sector organizations. Such transparency supports alignment between environmental commitments and effective corporate practices. Additionally, Almeida (2025) highlights that effective governance must integrate regulatory compliance, socio-environmental responsibility, and a commitment to operational efficiency—key elements given the complexity of managing intermittent energy sources.

Ultimately, the evidence examined indicates that curtailment reduction should not be viewed merely as a technical or operational issue, but rather as a strategic component of sustainable energy governance. Repeated curtailment undermines the attractiveness of renewable energy ventures, deters investors, and weakens the sector's ESG commitments (Rolim, 2025; Yang et al., 2020). The integration of technological solutions, sound governance practices, and coherent public policies proves essential for advancing the sustainability of the national energy matrix. Therefore, it is recommended that organizations and policymakers prioritize integrated and forward-looking initiatives, recognizing curtailment as a central factor in evaluating the quality of energy governance in Brazil.

IV. Discussion

The correlation between curtailment reduction and Environmental, Social, and Governance (ESG) practices reveals a central dilemma in the energy transition: despite increasing investments in renewable energy aimed at fulfilling environmental and social commitments, the conventional power infrastructure remains limited, preventing the full integration of intermittent generation and, consequently, undermining the realization of the intended environmental benefits. According to IRENA (2020), rising curtailment levels in systems with a high share of renewables negatively impact sustainability, as clean energy is wasted due to operational and regulatory failures.

Despite its significance, curtailment remains underestimated in the ESG indicators most commonly adopted. This omission reflects both normative and methodological gaps, since, as highlighted by Eccles, Ioannou, and Serafeim (2014), the effectiveness of ESG reporting depends on the specificity of the indicators used. The absence of metrics aimed at assessing avoidable energy losses may result in the overstatement of the positive environmental impacts reported by electric sector companies. In this context, energy governance must evolve to incorporate efficiency criteria in the use of renewable generation, moving beyond the mere quantification of installed capacity or avoided emissions.

The implementation of sustainable strategies — including energy storage, demand-side management, and grid expansion — faces technical, economic, and institutional obstacles. Studies conducted by Nycander et al. (2020) and Correia (2020) point to the high costs associated with storage systems, as well as the challenges in coordinating market actors. In Brazil, additional issues include rigid regulatory frameworks, delays in licensing procedures, and the absence of economic incentives for modernizing the electrical infrastructure — all of which perpetuate curtailment as a structural feature of the system.

To align ESG parameters with the challenges of the energy transition, it is essential to incorporate the concept of curtailment into evaluation and reporting processes. This can be achieved through three main avenues: (i) the development of specific indicators for avoidable energy losses; (ii) the recognition of technological initiatives aimed at reducing such losses; and (iii) the adoption of governance metrics that emphasize efficiency in infrastructure management. According to the IEA (2023), without such adjustments, energy governance may compromise the very principles of sustainability in the sector.

In this context, policymakers and corporate actors play a strategic role in the development and implementation of these indicators. Public-private partnerships, innovation incentive programs, and regulatory reforms focused on the effective integration of renewable sources represent promising alternatives to align ESG governance practices with the actual conditions of the energy sector.

Thus, by recognizing curtailment as a reflection of systemic inefficiencies rather than as an isolated failure, it becomes possible to develop more comprehensive assessment tools aligned with climate goals. Overcoming regulatory and technical barriers through integrated strategies involving government, the private sector, and society is essential to ensure the credibility and effectiveness of ESG commitments in the transition toward a truly sustainable energy system (Gomes et al., 2024; Troncoso, 2025; Rolim, 2025).

V. Conclusion

The research fully achieved all the previously established objectives, providing a detailed and strategic analysis of the relationship between the curtailment of renewable energy sources and the principles of Environmental, Social, and Corporate Governance (ESG). The general objective — to investigate this relationship and propose guidelines for a sustainable management of curtailment — was attained through a meticulous theoretical-analytical approach, grounded in a systematic review and a critical documentary analysis. The specific objectives were likewise fully met: the main causes and impacts of curtailment were examined (objective a); the role of ESG metrics in its mitigation was evaluated (objective b); and finally, integrative guidelines compatible with corporate environmental governance were proposed (objective c).

Regarding the theoretical framework, the study demonstrated in section 3.1 that curtailment stems from technical, regulatory, and structural factors, such as the intermittency of renewable energy sources, limitations in grid capacity, and shortcomings in energy planning. Furthermore, an upward trend in the occurrence of curtailment was identified in countries with high penetration of variable renewable energy sources, such as solar and wind, intensifying the need for both preventive and corrective strategies. In subsection 3.2, it was observed that, although curtailment still receives limited explicit attention in ESG guidelines, there is a growing recognition of the need to incorporate metrics related to energy efficiency, operational flexibility, and environmental responsibility as essential components in the management of the electric power sector. The present diagnosis highlighted the absence of international standards for evaluating curtailment in the context of ESG, while also indicating avenues for both conceptual and practical development. In section 3.3, the study proposed strategic guidelines encompassing policies aimed at decarbonization, modernization of energy infrastructure, adoption of storage technologies, and the digitalization of energy management — all of which were presented as promising alternatives to reduce curtailment in alignment with ESG principles.

The analytical contribution of this study was enhanced through the construction of tables and graphs that summarize the main results in an organized and comparative manner. Table 1 – Main Causes of Renewable Energy Curtailment enabled the identification — based on scientific and documentary evidence — of the technical, regulatory, and economic factors that most significantly influence the limitation of renewable energy generation. Table 2 – ESG Structures Addressing Energy Efficiency demonstrated how different ESG frameworks have begun, albeit tentatively, to address challenges related to energy efficiency and curtailment-related losses. Table 3 – Correlation Between ESG Adoption and Curtailment Reduction provided a comparative analysis of international experiences, indicating that entities and nations with greater adherence to ESG principles generally exhibit lower levels of curtailment, suggesting a positive association between environmental governance and efficiency in the power sector. Complementing this evidence, Table 4 – Strategic Guidelines for Curtailment Reduction compiles practical and scientifically grounded recommendations intended to guide policies and corporate actions focused on the sustainable mitigation of curtailment. Additionally, Figure 1 – Participation of Variable Renewable Energy Sources in Generation and Technical Curtailment in Selected Countries offered a graphical illustration of the discrepancy between the share of variable renewable energy (VRE) in national electricity mixes and technical curtailment rates, highlighting significant trends and underscoring the urgency for context-sensitive solutions.

As an extension of this research, it is suggested that future studies further explore the empirical analysis of the relationship between ESG practices and the reduction of curtailment in specific national and regional contexts, with an emphasis on case studies. Moreover, the development of ESG-specific metrics for energy losses is recommended to improve their measurement and management in accordance with sustainability criteria. Another promising area involves the investigation of the feasibility of emerging technologies aimed at curtailment mitigation, including advanced storage systems, smart grids, and artificial intelligence–based solutions. Lastly, it is recommended to analyze the economic impact of integrated curtailment management on the attractiveness of sustainable investments, considering ESG criteria as guiding parameters for investors and stakeholders. The intersection between technological innovation, public policy, and corporate governance constitutes a fertile ground for research aiming to overcome the obstacles posed by curtailment, thereby enabling a truly sustainable, inclusive, and resilient energy transition.

References

[1]. ANEEL. NATIONAL ELECTRIC ENERGY AGENCY (2020). *Regulatory adjustments for the implementation of hybrid power plants* – Improvement of regulation related to the contracting of access for multiple generating units – Regulatory Impact Report No. 002/2020 – SRG/SRT/SCG/ANEEL.

[2]. Almeida, V. (2025). Curtailment: The renewable generation cut and its impacts on the energy transition [Article on LinkedIn]. LinkedIn. Available at: https://www.linkedin.com/pulse/curtailment-o-corte-da-gera%25C3%25A7%25C3%25A3o-renov%25C3%25A1vel-e-seus-impactos-almeida-ryqlf/. Accessed: 05/2025.

[3]. Assunção, T. ESG and net zero emissions targets: accelerating climate action through private sector voluntary commitments in Brazil. *Revista Mosaicos*: Estudos em Governança, Sustentabilidade e Inovação, vol. 3, no. 1, pp. 17-34, 2021.

[4]. Bezerra, F. D. (2023). Banco do Nordeste. Industry. *Green Hydrogen:* Opportunity for the Northeast. ETENE Sectorial Notebook. Year 8. No. 320. Dec.

[5]. Castro, N. de et al. (2022). The growing importance of flexibility resources in the face of the accelerated expansion of variable renewable sources: the role of energy storage. Rio de Janeiro: GESEL/UFRJ. ISBN: 978-65-86614-62-6.

[6]. Correia, T. de B. C. (2020). *Energy Systems of the Future:* Regulatory solutions for reduction or limitation of generation in real-time operation. Brasília: MME/ANEEL.

[7]. Cruz, A. C. da S. O. da; Medeiros, A. F. de. (2021). Theoretical-methodological construction of a research: an analysis of the path traveled. *Research, Society and Development*, vol. 10, no. 17, e244101724708. (CC BY 4.0). ISSN 2525-3409. http://dx.doi.org/10.33448/rsd-v10i17.24708.

[8]. Eccles, R. G., Ioannou, I., & Serafeim, G. (2014). The impact of corporate sustainability on organizational processes and performance. *Management Science*, 60(11), 2835-2857. https://doi.org/10.1287/mnsc.2014.1984

[9]. Gomes, R. L. R. et al. (2024). Corporate Education And ESG Practices: People Management Strategies To Strengthen Citizenship And Sustainability Within Organizations. *IOSR Journal of Business and Management* (IOSR-JBM) e-ISSN: 2278-487X, p-ISSN: 2319-7668. Volume 26, Issue 11. Series 4 (November), pp. 50-55. http://dx.doi.org/10.9790/487X-2611045055

[10]. Gould, R. (2017). Data literacy is statistical literacy. *Statistics Education Research Journal*, vol. 16, no. 1, pp. 22-25.

[11]. Guerra, A. de L. e R., Stroparo, T. R., Costa, M. da, Castro Júnior, F. P. de, Lacerda Júnior, O. da S., Brasil, M. M., & Camba, M. (2024). Qualitative research and its fundamentals in scientific investigation. *Journal of Management and Secretariat*, 15(7), e4019. https://doi.org/10.7769/gesec.v15i7.4019

[12]. Guevara, A. J. de H.; Dib, V. C. ESG principles, challenges and opportunities. *RISUS – Journal on Innovation and Sustainability*, São Paulo, vol. 13, no.4, pp. 18-31, Nov./Dec. 2022. ISSN 2179-3565. http://dx.doi.org/10.23925/2179-3565.2022v13i4p18-31.

[13]. IEA (International Energy Agency). (2023). *Renewable Energy Market Update Outlook for 2023 and 2024.* Paris. Available at: https://iea.blob.core.windows.net/assets/63c14514-6833-4cd8-ac53-f9918c2e4cd9/RenewableEnergyMarketUpdate_June2023.pdf. Accessed: 05/2025.

[14]. Intergovernmental Panel on Climate Change (IPCC). (2012). *Special Report on Renewable Energy Sources and Climate Change Mitigation.* Available at: https://www.ipcc.ch/site/assets/uploads/2018/03/SRREN_FD_SPM_final-1.pdf Accessed: May 19, 2025.

[15]. International Renewable Energy Agency (IRENA). (2018). *Power System Flexibility for the Energy Transition.* Part 1: Overview for Policy Makers. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/%20%20%20Publication/2018/Nov/IRENA_Power_system_flexibility_1_2018.pdf Accessed: May 17, 2025.

[16]. IRENA. (2020). *Electricity Storage Valuation Framework:* Assessing system value and ensuring project viability. International Energy Agency.

[17]. Joskow, P. L. (2019). Challenges for wholesale electricity markets with intermittent renewable generation at scale: the US experience. *Oxford Review of Economic Policy*, 35(2), pp. 291–331.

[18]. Lima Junior, E. B. et al. (2021). Documentary Analysis as a Methodological Path in Qualitative Research. *Cadernos da Fucamp*, vol. 20, no. 44, pp. 36-51.

[19]. Luz, T. J., & Vila, C. U. (2024). Generation and transmission expansion planning with full-year hourly power balance. *Brazilian Archives of Biology and Technology*, 67, e24231004. https://doi.org/10.1590/1678-4324-2024231004

[20]. Machado, P. K. O., & Checon, B. Q. (2023). Analysis of compliance with corporate governance criteria by companies referred to as environmental, social, and governance (ESG). FGV. *RIC Scientific Initiation Journal*, 4(1).

[21]. Murasawa, L. (2022). Climate change; carbon market. In C. Arruda (Ed.), *The role of companies in the ESG environmental agenda*. Fundação Dom Cabral.

[22]. Nunes, K. R., et al. (2024). Applicability of green energies for corporate sustainability: perspectives for social, environmental, and corporate governance (ESG). *IOSR Journal of Business and Management (IOSR-JBM),* 26(10, Series 7), 49–53. https://doi.org/10.9790/487X-2610074953

[23]. Nycander, E., Söder, L., Olauson, J., & Eriksson, R. (2020). Curtailment analysis for the Nordic power system considering transmission capacity, inertia limits, and generation flexibility. *Renewable Energy*, 152, 942–960. https://doi.org/10.1016/j.renene.2020.01.093

[24]. O'Shaughnessy, E., Cruce, J., & Xu, K. (2021). Solar PV curtailment in changing grid and technological contexts [Preprint]. *National Renewable Energy Laboratory*. https://www.nrel.gov/docs/fy21osti/74176.pdf

[25]. Pinho, L. (2017). *Evaluation of hydrogen production from wind energy surpluses using multi-objective evolutionary algorithms.* [Master's thesis, Federal University of Rio de Janeiro, Alberto Luiz Coimbra Institute for Graduate Studies and Research in Engineering].

[26]. Pontes, A. S. (2024). Green hydrogen production from surpluses of wind farms in the state of Ceará – Brazil. *Research, Society and Development*, 13(10), e110131047180. https://doi.org/10.33448/rsd-v13i10.47180

[27]. Ribeiro, N. C. (2021). Instrument for critical analysis of research reports: theses and dissertations. *Encontros Bibli: Electronic Journal of Librarianship and Information Science*, 26, 1–25. https://doi.org/10.5007/1518-2924.2021.e78678

[28]. Rolim, J. (2025). *Renewable generation curtailment:* 10 reasons that justify compensation to producers [LinkedIn post]. https://www.linkedin.com/posts/joaquimrolimjcro_no-cortes-de-gera%C3%A7%C3%A3o-renov%C3%A1vel-curtailment-activity-7311478654943830016-EfaL/?originalSubdomain=pt

[29]. Schierenbeck, A. (2025). The cost of inaction: Grid flexibility for a resilient, equitable digital energy future. *World Economic Forum.* https://www.weforum.org/stories/2025/01/grid-flexibility-for-resilient-equitable-digital-energy-future/

[30]. Seiler, P., & Hoyt, J. (2020). Wind farm wake-steering exploration during grid curtailment. In *American Control Conference*.

[31]. Troncoso, F. (2025). *Curtailment in Brazil and lessons from global solutions:* turning challenges into opportunities [LinkedIn post]. https://www.linkedin.com/pulse/curtailment-brasil-e-li%C3%A7%C3%B5es-de-solu%C3%A7%C3%B5es-globais-em-franco-troncoso-7wvlf/

[32]. Valente, M. C., Sobrosa, T., & Terra, J. (2024). Energy curtailment: why generation limitation is a reality in Brazil. *EXAME Magazine*. https://exame.com/esg/curtailment-de-energia-por-que-a-limitacao-da-geracao-e-uma-realidade-no-brasil/?utm_source=copiaecola&utm_medium=compartilhamento

[33]. Vieira, G. V. (2022). *Energy efficiency through the implementation of ESG culture* [Undergraduate thesis, São Paulo State University]. UNESP.

[34]. Yang, R. L., et al. (2020). Efficient management of electric power generation: challenges for reducing renewable energy curtailment. *Brazilian Journal of Energy*, 26(1). https://doi.org/10.47168/rbe.v26i1.5626.