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Nanostructured Solutions for Energy Sustainability: Interfaces Between Technological Innovation, Accessibility, and Climate Mitigation

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ABSTRACT
In light of global challenges concerning energy security, social inclusion, and climate change mitigation, the pursuit of sustainable technological solutions has intensified in recent decades. Within this context, nanotechnology emerges as a promising field, particularly due to its applications in renewable energy sources. The advancement of materials and devices at the nanoscale has led to significant improvements in the efficiency, accessibility, and sustainability of energy technologies, directly contributing to the United Nations Sustainable Development Goals (SDGs). The methodology employed in this study is qualitative in nature, based on bibliographic and documentary research procedures. The methodology adopted in this research is qualitative in nature, employing bibliographic and documentary research procedures. A total of forty-one scientific works and several national and international documents on the subject were analyzed, enabling a critical and up-to-date approach to the topic under investigation. The main objective of this study is to analyze how nanostructured solutions applied to renewable energy can contribute to energy sustainability by fostering technological

innovation, enhancing energy accessibility, and mitigating the impacts of climate change, in alignment with the UN SDGs. The findings of the research demonstrate that nanotechnologies applied to renewable energies hold substantial potential to increase the energy efficiency of devices, expand access to clean energy in vulnerable contexts, and promote the decarbonization of the energy matrix. These results underscore the relevance of nanotechnology as a strategic tool for addressing climate change and advancing renewable energy development.

Keywords: *nanotechnology; renewable energy; energy sustainability; climate change.*

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I. INTRODUCTION

The search for cleaner, more efficient, and more accessible energy sources has taken on a central role in the global landscape due to the intensification of climate change and the urgent need to implement a sustainable energy transition. In this scenario, renewable energy sources—such as solar, wind, and biomass—have emerged as promising alternatives for the gradual replacement of fossil fuels, helping to reduce greenhouse gas emissions and mitigate the environmental impacts associated with conventional energy matrices. However, the effectiveness and widespread adoption of these renewable sources depend on technological advancements capable of improving the conversion, storage, and distribution of energy in an efficient, durable, and economically viable manner.

In this context of innovation and sustainability, nanotechnology has established itself as a key field in the development of more efficient energy solutions, enabling the manipulation of matter at atomic and molecular levels to create new materials with enhanced properties. These nanostructured solutions have been applied in photovoltaic devices, fuel cells, supercapacitors, lithium-ion batteries, and carbon capture and conversion systems, contributing significantly to improvements in energy efficiency, system durability, and production cost reduction. Furthermore, these technologies promote the democratization of energy access in vulnerable areas and support the achievement of the Sustainable Development Goals (SDGs), particularly those related to clean and affordable energy (SDG 7), innovation and infrastructure (SDG 9), and global climate change mitigation (SDG 13) (UN, 2021).

The methodology employed in this study is distinguished by its qualitative approach, which is essential for a thorough and critical understanding of the interactions between science, technology, the environment, and society. Two complementary investigative procedures were utilized: bibliographic research, supported by forty-one scientific works, including articles and theses; and documentary research, based on the analysis of both national and international documents that regulate and guide the development of nanotechnology as well as climate and energy policies. Methodological triangulation enabled an integrated analysis of the scientific and regulatory aspects of nanostructured solutions aimed at energy sustainability.

The general objective of this research is to analyze how nanostructured solutions applied to renewable energies can contribute to energy sustainability by fostering technological innovation, enhancing energy accessibility, and mitigating the impacts of climate change, in alignment with the United Nations Sustainable Development Goals (SDGs). The specific objectives are to: (1) investigate the main advances in nanotechnology related to the development of materials and devices used in renewable energy sources; (2) assess the potential of nanostructured solutions to expand access to sustainable energy technologies in socially vulnerable contexts; and (3) understand how nanotechnological solutions contribute to the energy transition, the reduction of greenhouse gas emissions, and the response to climate change.

This article is organized into four sections. The first presents the introduction, outlining the research context, methodology, and study objectives. The second section addresses the methodological aspects, detailing the qualitative approach and the procedures used. The third section comprises the theoretical framework, discussing the interfaces between nanotechnology, renewable energies, and energy sustainability. Finally, the fourth section presents the final considerations, summarizing the main findings and suggesting directions for future research.

II. MATERIAL AND METHODS

The methodology adopted for the development of this research is distinguished by its qualitative nature, whose scientific relevance lies in its capacity to provide a deep and contextualized understanding of social, technological, and environmental phenomena. According to Lakatos and Marconi (2019), qualitative research transcends mere quantification and aims to interpret meanings, interrelations, and underlying structures within the data, thus proving particularly effective in studies focused on technological innovations and their socio-environmental impacts. This methodological approach enables a nuanced comprehension of the complex and interrelated dimensions of nanostructured solutions aimed at energy sustainability, in alignment with the United

Nations Sustainable Development Goals (SDGs), while considering not only technical aspects but also their political, social, and environmental implications.

The methods employed consisted of bibliographic and documentary research. The bibliographic research was based on forty-one scientific works, including articles published in specialized journals accessed through scientific databases such as SciELO, Google Scholar, and CAPES journals, as well as doctoral theses. This provided a solid and contemporary theoretical foundation. According to Pereira et al. (2018), this type of approach is essential to global science, as it enables the organization of existing knowledge, the identification of theoretical gaps, and the orientation of new research initiatives. The documentary research, in turn, was grounded in the analysis of national and international documents relevant to the topic, including reports from the Intergovernmental Panel on Climate Change (IPCC, 2022), the Nanotechnology Action Plan by the Ministry of Science, Technology and Innovations (MCTIC, 2019), the Project no. 880/2019 (Brasil, 2019), the Guidelines for a National Strategy for Climate Neutrality (MMA, 2022), the United Nations document (2021) Progress towards the Sustainable Development Goals – Report of the Secretary-General, and the report from the Brazilian Senate Agency (2020) on the Legal Framework for Nanotechnology. These documents enabled a comprehensive understanding of the regulatory and policy frameworks that underpin the advancement of nanotechnology both in Brazil and internationally, as well as their relation to climate change mitigation and the promotion of energy sustainability.

According to Grazziotin, Klaus, and Pereira (2022), the combination of documentary and bibliographic research constitutes a powerful methodological tool for scientific advancement, as it allows not only the organization of established knowledge but also the critical assessment of evolving guidelines, public policies, and legal frameworks. In this context, the articulation between bibliographic and documentary sources fostered a deeper analytical approach, allowing for an integrated interpretation of the scientific, technological, regulatory, and socio-environmental aspects associated with the application of nanotechnologies in energy solutions aimed at decarbonization and climate equity.

This assertion is substantiated by the diversity of high-level materials and research, classified as Qualis A1/L1, published by the American Chemical Society (2022) in the ACS Symposium Series (Vol. 1421). This volume compiles chapters from various international researchers who address topics ranging from the design, evaluation, and applications of nanostructured materials for sustainable energy, as highlighted in the thematic areas presented in the table below:

Table 1 – Thematic Highlights from the ACS (2022) Book Chapters

Chapter Topic	Sustainable Application	Utility
2D MPX_3 Materials	Photocatalysis, batteries, membranes	Two-dimensional (2D) materials for catalysis, energy storage and conversion, such as metal phosphorus trichalcogenides (MPX_3), with applications in photocatalysis, electrocatalysis, batteries, and membranes.
Nanostructured electrocatalysts for H_2 production	Green hydrogen, fuel cells	Interactive nanomaterials for energy storage and conversion, including electrocatalysts for hydrogen production and high energy density supercapacitors.
Organic carbon-based composites for electrodes	Supercapacitors, energy storage	Organic-carbon composites for next-generation capacitive electrodes, highlighting active redox materials and sustainable fabrication methods.
Metallic chalcogenides via ALD	Electrocatalysis (HER, OER, ORR)	Synthesis of iron, cobalt, and nickel chalcogenides via atomic layer deposition for electrocatalysis applications (HER, OER, ORR).
WS_2 nanomaterials for photocatalysis	Pollutant degradation under visible light	Advanced photocatalysis with tungsten disulfide (WS_2) nanomaterials for the degradation of organic pollutants under visible light.
Dry reforming of methane with nanostructured catalysts	CO_2 /CH_4 conversion into low-carbon syngas	Solar-assisted dry reforming of methane using nanostructured catalysts, converting CO_2 and CH_4 into low-carbon syngas.

Nanofluids for solar collectors	Efficiency in solar heating and cooling	Nanofluid strategies for solar collectors with dual heating/cooling function, improving energy efficiency in urban environments.

Source: ACS (2022)

This table provides a concise and structured overview of various types of advanced materials and their sustainable applications, emphasizing their relevance in the development of clean and efficient technologies. It highlights how nanomaterials, organic carbon-based compounds, and innovative catalysts contribute to the implementation of more sustainable energy solutions, such as green hydrogen production, supercapacitors, and solar collectors. Furthermore, it underscores the importance of advanced manufacturing methodologies, such as atomic layer deposition (ALD), in creating high-performance materials with a reduced environmental impact. This synthesis is particularly valuable for researchers exploring technological options aligned with the Sustainable Development Goals (SDGs).

III. LITERATURE REVIEW

3.1 Nanotechnology and Renewable Energy: Advances in Materials and Devices for Energy Efficiency

In the realm of technological innovation and climate mitigation, the United Nations, through the establishment of the Sustainable Development Goals (SDGs), defined in SDG 7 the objective of ensuring access to reliable, sustainable, modern, and affordable energy for all by 2030. Among its aims, the goal emphasizes strengthening international cooperation to facilitate access to research and clean energy technologies, including renewable energy and energy efficiency (UN, 2015).

Within the technological framework of the UN's SDG 7 (2015), nanotechnology emerges as a foundational pillar of scientific innovation directed toward energy sustainability, particularly in the context of renewable energy. Its significance lies in the manipulation of matter at the nanometric scale, enabling remarkable advancements in the conversion, storage, and transportation of energy. The Action Plan for Science, Technology, and Innovation in Converging and Enabling Technologies (Brazil, 2019) identifies nanotechnology as one of the country's strategic priorities, underscoring its relevance to energy and environmental challenges. In this context, nanoengineered solutions applied in photovoltaic systems, wind turbines, thermoelectric devices, and fuel cells have emerged as promising technological alternatives to facilitate a sustainable energy transition.

One of the most notable breakthroughs concerns the development of functional carbon-based nanomaterials, such as graphene, nanotubes, and quantum dots, which have exhibited exceptional thermal, electrical, and optical conductivity properties. According to Li et al. (2019), these materials play a fundamental role in photovoltaic devices and supercapacitors, significantly enhancing energy capture and storage efficiency. Moreover, the combination of metallic and semiconductor nanoparticles allows for spectral response tuning in solar cells, thereby increasing the absorption capacity of both visible and infrared light. Jeevanandam et al. (2018) stress that, despite their high performance, the regulatory aspects and potential toxicity of these nanomaterials must be thoroughly assessed to ensure that innovation progresses in a safe and responsible manner.

A particularly promising innovation relates to the transformation of low-energy photons into usable energy through the upconversion technique, which employs nanoengineered semiconductor structures to optimize solar harvesting. As noted by Chen et al. (2018), this methodology has the potential to overcome the theoretical efficiency limits of conventional photovoltaic systems, allowing for more effective solar radiation utilization under various climatic conditions. Nanoengineered materials are being enhanced to exhibit tunable dielectric properties, as demonstrated by Oh et al. (2019), who investigated the production of zirconia using NanoParticle Jetting™ technology for applications in energy device substrates. The implications of these innovations are summarized in the following table, which outlines the energy applications of nanomaterials as identified by Li et al. (2019):

Table 2 – Applications of Carbon-Based Nanomaterials in Renewable Energy

Nanomaterial	**Properties**	**Energy Application**
Graphene	High electrical conductivity, large surface area	Supercapacitors, 11ransparente electrodes
Carbon Nanotubes (CNTs)	Thermal stability, mechanical strength	Hydrogen storage, batteries

Quantum Dots	Tunable bandgap, high photoluminescence	Solar cells, photocatalysts
Carbon Dots	Low toxicity, biocompatibility	Bioenergy systems, light harvesting

Source: Li et al. (2019)

Another significant aspect of the implementation of nanotechnology in the energy sector concerns production methods and materials engineering. Oh et al. (2019) demonstrated that manipulating microstructures through additive techniques enables the modulation of the dielectric properties of nanostructured ceramic materials, which directly influences the miniaturization and performance of components in energy conversion systems. The flexibility of these procedures allows for the creation of lighter, more efficient, and adaptable devices, suited to various geographical and socioeconomic contexts, thereby promoting energy accessibility—one of the foundational pillars for achieving the Sustainable Development Goals (SDGs) established by the United Nations (2021). The Argonne National Laboratory (USA, 2024) hosted a scientific event dedicated to discussions on Nanoengineering Materials for Energy Applications, addressing topics that reflect the state of the art in nanostructured solutions for sustainable energy. These themes, frequently featured in high-impact journals such as ACS Nano, Advanced Energy Materials, and Nano Energy, are highly relevant for future research in the field, including: Two-dimensional materials with controlled interlayer spacing for lithium-ion batteries and supercapacitors. Discovery of active sites at metal-oxide interfaces for green hydrogen production. Research on sustainable hydrogen production at the Center for Nanoscale Materials. Application of nanoscience to catalysis, conversion, and storage of clean energy. Finally, it is essential to emphasize that the implementation of nanostructured solutions must not occur in isolation but in alignment with public policies, regulatory frameworks, and investments in scientific training.

The volume edited by Fechine (2020) compiles various studies on recent advances in nanomaterials and underscores the importance of fostering synergy between research, innovation, and technology transfer. This integration is crucial to ensuring that nanotechnology effectively contributes to mitigating the effects of climate change, thereby fostering a more sustainable, equitable, and resilient energy future.

3.1.1 Nanomaterials in Advanced Energy Storage

Integrating intermittent renewable sources, such as wind and solar, into the global energy matrix requires the efficiency of storage systems, as well as the durability and accessibility of such equipment. In this context, nanomaterials emerge as a transformative tool to enable significant changes in supercapacitors and batteries. For example, lithium-ion batteries with nano-structured silicon anodes, which offer higher energy density compared to conventional graphite electrodes, also provide stability in their charge/discharge cycles (Khan et al., 2021). These advancements enable the existence of more compact and durable batteries, ideal for applications in microgrids and remote communities, thus serving as a tool for energy accessibility in line with SDG 7 (United Nations, 2016).

Beyond batteries, nanomaterial-based supercapacitors, such as graphene and MXenes, stand out for their ultrafast charge/discharge capability and high-power density. According to Zhang et al. (2023), MXenes, a class of two-dimensional materials, are exceptionally known for their electrical conductivity and considerable surface area, placing them in a promising position for composing smart energy storage networks and being part of electric vehicle technologies. These characteristics reduce system maintenance costs, thereby increasing reliability in regions affected by electrical grid instability and creating an environment of energy equity.

Continuing with technological development, hybrid systems combining nano-structured batteries and supercapacitors are observable, optimizing energy storage and meeting diverse energy consumption demands. According to Reveles-Miranda, Ramirez-Rivera, and Pacheco-Catalán (2024), hybrid energy storage systems make it possible to combine energy and power-based storage, thereby improving technical characteristics and providing additional benefits in energy supply to remote areas or regions with limited energy networks, demonstrating both their technical feasibility and positive social impact. As a result of such implementations, energy efficiency through innovative tools aligns with the ideals of SDG 9 and SDG 13, promoting innovative technology and enabling the decarbonization of energy matrices through highly reliable renewable sources.

However, scaling these technologies requires aligning the production costs of nanomaterials with the development of environmental regulation policies aimed at ensuring the security of the environmental agenda. Sustainable synthesis methodologies must be explored, implementing nanomaterial recycling to link energy benefits with sustainable principles (Adeyinka et al., 2024). Integrating these solutions with public policies and fiscal incentives, such as those proposed in the Brazilian Nanotechnology Legal Framework (Brazil, 2016), will be crucial for their widespread adoption in Brazil and other developing countries.

To illustrate the advantages of nanostructured technologies in energy storage, Table 4 compares nanomaterial-based batteries, supercapacitors, and hybrid systems with their conventional counterparts, highlighting benefits in efficiency, accessibility, and sustainability.

Table 3 – Comparative analysis of nanomaterial-based energy storage technologies versus conventional ones.

Aspect	Conventional Technologies	Technologies Based on Nanomaterials	Advantages of Nanomaterials
Technology	Lithium-ion batteries (graphite electrodes)	Lithium-ion batteries with silicon or nano-structured anodes	Higher energy density (~3x higher). Longer life cycles (Khan et al., 2021). Ideal for microgrids in remote areas.
	Supercapacitors with activated carbon electrodes	Supercapacitors with graphene or MXenes	Ultrafast charge/discharge. High power density. Greater durability (Zhang et al., 2023)
	Isolated storage systems (traditional batteries)	Hybrid systems (batteries + nanostructured supercapacitors)	Combination of high energy and power. Better adaptation to variable demands and use in remote areas (Reveles-Miranda; Ramirez-Rivera; Pacheco-Catalán, 2024).
Energy efficiency	Moderate (significant losses in charge/discharge cycles)	High (lower losses due to greater conductivity and surface area)	Reduced energy losses, increasing efficiency in renewable systems
Durability	Limited cycles (~500–1000 cycles for traditional batteries)	Extended cycles (~2000–5000 cycles for nano-structured batteries; >10000 for supercapacitors)	Less need for replacement, reducing maintenance costs
Production cost	Relatively low, but with less efficient materials	Initially higher, but reduced with scalability and new synthesis techniques	Potential for long-term cost reduction with advanced manufacturing (e.g., 3D printing)
Accessibility	Limited in remote areas due to weight, size, and required infrastructure	High, with more compact and adaptive devices for microgrids and decentralized systems	Facilitates access to clean energy in underserved communities (SDG 7)
Environmental impact	Higher impact due to intensive mining and non-recyclable materials	Lower impact with recyclable nanomaterials, but requires regulation for toxicity	Contributes to decarbonization and sustainability (SDG 13)
Practical applications	Urban power grids, large-scale electronic devices	Rural microgrids, electric vehicles, battery backup systems in unstable grids	Versatility for various uses, promoting energy equity

Source: Adapted from Khan et al. (2021), Zhang et al. (2023), Reveles-Miranda, Ramirez-Rivera, and Pacheco-Catalán (2024), and Adeyinka et al. (2024).

Table 3 provides a clear and concise analysis of the distinctions between conventional energy storage technologies and those based on nanomaterials. The author emphasizes how advancements in nanotechnology have led to remarkable improvements in areas such as energy efficiency, durability, accessibility, and environmental impact. Furthermore, the capacity of these technologies to promote greater energy equity—especially in remote regions—and to support the achievement of global sustainability goals, such as the United Nations Sustainable Development Goals (SDGs), is underscored. This represents a significant resource for understanding the benefits of nanomaterials in the transition toward more efficient and sustainable energy systems.

3.2 Energy Accessibility and Social Inclusion: The Role of Nanostructured Technologies in the Democratization of Clean Energy

The search for sustainable alternatives for energy production and distribution has fostered the advancement of nanostructured technologies, particularly in contexts marked by social and energy-related vulnerabilities. Within this framework, nanomaterials emerge as promising tools to expand access to clean, efficient, and affordable energy, thereby contributing to social inclusion and the reduction of inequalities. According to Oliveira (2018), the development of nanomaterials aimed at enhancing smart grid infrastructures has enabled greater stability and efficiency in energy distribution, reaching even remote or peripheral regions—constituting a significant step toward energy democratization.

The ability of nanostructured solutions to link intermittent renewable sources such as solar and wind power to efficient storage systems is another essential factor in ensuring energy accessibility. Garcia and Silva (2020) emphasize that microgrids integrated with storage systems based on nanotechnology enable energy self-sufficiency in remote communities while promoting the decentralization of the electrical grid. The use of innovative materials in batteries, as highlighted by Khan et al. (2021), enhances the autonomy and longevity of such devices, establishing them as strategic alternatives in contexts where conventional power grids are ineffective or unavailable.

Public policy and incentives for technological innovation play a crucial role in this regard. The Economic Commission for Latin America and the Caribbean (ECLAC) and the Center for Strategic Studies and Management (CGEE, 2020) underscore the importance of promoting policies that support the research and development of clean energy technologies with the potential for large-scale, cost-effective deployment. Aligned with ECLAC and CGEE, the National Confederation of Industry (CNI) released the Strategic Industry Map, stating that the transition to a low-carbon economy will require the combined efforts of the public and private sectors to implement actions, programs, and technologies aimed at decarbonizing the country (CNI, 2023).

In this context, nanotechnology once again proves to be a strategic ally by enabling the production of more affordable and high-performance devices adapted to the diverse social and environmental conditions in Brazil. Thus, the alignment of innovative technology with social equity becomes feasible through organized mechanisms of research support and financial investment.

Beyond the technical and political dimensions, the socio-environmental changes driven by nanostructured solutions demand an interdisciplinary approach. In her study on the implementation of low-emission buses in Brazil, Bermúdez (2018) highlights how technological innovations in energy systems can reconfigure urban dynamics and mobility patterns. This perspective emphasizes that the energy transition extends beyond the technological domain and includes cultural, social, and economic dimensions that must be considered when designing inclusive policies. In this sense, access to clean energy should be regarded as a fundamental right and an essential condition for sustainable human development.

In this context, the importance of nanomaterials such as TiO_2 , which is employed as a photocatalyst in hydrogen production, is particularly noteworthy. As demonstrated by Silva and Alves (2021), the generation of green hydrogen through accessible photochemical processes can serve as a viable energy solution for communities with limited access to other sources. Fontana et al. (2024) further assert that the use of these materials can be scaled to various applications, from residential systems to community energy plants. The flexibility of these technologies highlights their adaptability to the specific needs of populations in vulnerable situations.

Based on the contributions of Fechine (2020), it is possible to identify a set of nanomaterial innovations that enable the development of devices that are both energy-efficient and economically accessible. The following table, to be placed at the end of the fourth paragraph, provides a summary of key applications of nanomaterials aimed at energy inclusion, with an emphasis on decentralized and sustainable energy generation in socially vulnerable contexts.

Table 4 – Applications of Nanostructured Materials for Energy Access in Vulnerable Contexts.

Nanomaterial Type	**Energy Application**	**Social Impact**
Nanostructured TiO_2	Photocatalytic hydrogen generation	Clean fuel production for off-grid communities
Carbon-based Nanotubes	Solar cell efficiency enhancement	Low-cost photovoltaic solutions for rural areas

Nanostructured Ceramics	Thermal energy storage	Improved cooking and heating systems in poor regions
Flexible Nanomaterials	Wearable solar panels	Mobile energy for itinerant populations
Nano-enabled Supercapacitors	Rapid charge/discharge energy storage	Reliable power backup in areas with grid instability

Source: Fechine (2020)

Braga (2024), in his article, discusses public policies aimed at renewable energy in Brazil—a topic that has gained increasing prominence. Access to clean energy in remote and low-income communities is a central aspect for promoting energy accessibility and social inclusion. In this context, public policies and technological innovations play a vital role, particularly the application of nanostructures, which aim to expand access to and the sustainability of energy systems.

Gonzalez et al. (2023) note that the right to access clean energy in Brazil is underpinned by a regulatory framework and its constitutional recognition, both of which ensure the presence of clear public policies that reinforce the legitimacy and effectiveness of efforts aimed at enhancing energy accessibility.

Major international agencies—such as the World Health Organization (WHO), the International Energy Agency (IEA), the United Nations (UN), and the International Renewable Energy Agency (IRENA)—recently published the *Tracking SDG 7: The Energy Progress Report 2023* (WHO, IEA, UN, & IRENA, 2023). This document presents updated data on global access to electricity, highlighting that 675 million people still live without electricity and 2.3 billion lack access to clean cooking solutions. The report further emphasizes the need to ensure universal access to reliable and affordable energy services.

The integration of nanotechnological innovation with public policies focused on energy inclusion may thus constitute an effective approach to achieving the United Nations Sustainable Development Goals (SDGs) (UN, 2021). Beyond their promise in the technological realm, nanostructured solutions fulfill a political and social transformative role, contributing to a fair, equitable, and sustainable energy transition. To achieve SDG 7 by 2030, it is essential to invest in clean and affordable energy sources.

3.3 Nanotechnology and the Energy Transition: Contributions to Decarbonization and the Fight Against Climate Change

Nanotechnology is emerging as one of the main enablers of the global energy transition by facilitating the development of advanced materials that enhance the efficiency of renewable energy sources and contribute to the reduction of greenhouse gas emissions. Research conducted by Manickam et al. (2021) highlights that the use of nanomaterials in bioenergy and biofuel systems represents a significant advancement in clean energy conversion by optimizing reaction kinetics and process stability. Similarly, Das et al. (2022) underscore the application of nanoparticles in environmental remediation, pointing out that such solutions not only promote sustainability but also mitigate the environmental impacts of human activities.

These strategies align with the guidelines set by the Intergovernmental Panel on Climate Change (IPCC, 2022), which emphasize the urgent need for sustainable and innovative technologies to address climate change-related challenges. In line with the Paris Agreement and the 2030 Agenda, the IPCC also released a report containing a broad range of information on climate change, recognizing the interdependence between climate, ecosystems, biodiversity, human societies, and sustainable development. The report stressed that combating the effects of global warming requires the adoption of mechanisms that improve access to financing and technologies—critical for effective climate action—which underscores the need for R&D investment in nanostructured technologies (IPCC, 2023).

In the Brazilian context, there has been a progressive move towards regulation and encouragement of nanotechnology adoption in strategic sectors such as energy. According to the Agência Senado (2020) and Bill No. 880/2019, the implementation of a Legal Framework for Nanotechnology is under debate, aiming to promote research, technological development, and innovation in this field. Rodrigues (2024) argues that by integrating incentive mechanisms with tax benefits, Brazil can establish a solid path toward climate neutrality. This legislative framework aims not only to attract investment but also to establish a science policy focused on energy sustainability, in line with the United Nations Sustainable Development Goals (UN, 2021).

The contribution of nanotechnology to decarbonization extends beyond material advancements; it also plays a strategic role in public policies aimed at climate change mitigation. According to the Ministry of the Environment (2022), the National Strategy for Climate Neutrality acknowledges the importance of emerging technologies, including nanomaterials, in enabling more sustainable production processes. In this context, Berger

Filho and Silveira (2020) highlight the need for effective governance to manage the associated risks, ensuring that the benefits are not undermined by regulatory gaps. Thus, nanotechnology governance must be aligned with the advancement of innovation while ensuring safety, ethics, and justice.

The convergence between nanotechnology and the energy transition is also reflected in international forums. During COP 27, Garcia (2023) emphasized the importance of fair and actionable solutions for the energy transition, stressing that nanostructured technologies offer a promising avenue for diversifying the energy matrix, particularly in developing countries. Such technologies not only broaden access to clean energy but also drive more resilient development models. Ahire et al. (2022) support this view by noting that nanotechnology is a versatile tool with wide applicability in low-emission contexts, from energy generation to storage and transportation.

However, the issue of waste disposal resulting from nanomaterial applications remains a concern. Improper solid waste management—including nanomaterials—can lead to soil and water contamination, negatively impacting ecosystem services for the population, productive sectors, and biodiversity. Paschoalino et al. (2010) found in their research that nanomaterials can have adverse effects on biodiversity, affecting air, soil, and water quality, and potentially leading to the extinction of animal and plant species. Although the interactions between nanomaterials and environmental receptor organisms are not yet fully understood, there is evidence suggesting that they may cause toxicity and bioaccumulation in aquatic and terrestrial species.

Table 5 – Key Actions and Technologies for a Just Energy Transition Supported by Nanotechnology

Actionable Area	**Nanotechnology Contribution**	**Impact on Climate Goals**
Renewable Energy Generation	Nanostructured solar cells and catalysts for biofuels	Enhanced efficiency and scalability
Energy Storage	Nano-enabled batteries and supercapacitors	Greater energy reliability and grid balance
Environmental Remediation	Nanoparticles for pollutant capture and CO_2 sequestration	Reduction of GHGs and ecosystem recovery
Decentralized Access	Low-cost nano-solar panels and materials	Energy equity in underserved regions

Source: Garcia (2023)

The formalization of public policies that promote the safe and conscious use of nanotechnology is, therefore, essential to ensure that technological innovations translate into tangible benefits for society and the environment. The Legal Framework for Nanotechnology, as presented in Brazil (Brasil, 2019), provides a regulatory context conducive to encouraging investment in research, innovation, and scientific training. However, as Rodrigues (2024) emphasizes, it is imperative that ongoing efforts are made to link such policies to sustainability goals and climate neutrality. By integrating science, technology, and social responsibility, Brazil strategically positions itself at the forefront of the global energy transition.

The IRENA (2021) report on the global energy transition highlights the relevance of innovative solutions and emerging technologies for achieving global climate targets. Although it does not delve deeply into nanotechnology in academic studies, it does refer to technological advances that contribute to this goal. The World Energy Transitions Outlook outlines a strategic roadmap for achieving the objectives of the Paris Agreement, reducing the impact of climate change, and transforming the global energy landscape. The document explores alternatives to limit temperature rise to 1.5°C and achieve net-zero CO_2 emissions by 2050. Moreover, it presents a comprehensive view of the necessary technological choices, investments, public policies, and socioeconomic impacts required to ensure sustainability, resilience, and an inclusive energy system.

Ultimately, the energy transition based on nanostructured solutions must be understood as a multidimensional process that encompasses both the enhancement of technical and scientific skills and the promotion of access to clean energy. The vision of a sustainable future requires the adoption of innovative technologies that deliver not only economic and environmental benefits but also social equity. In this context, nanotechnology emerges as a crucial element in addressing climate change, aligning with the international commitments assumed by the country and the emerging demands of an evolving society.

IV. DISCUSSION AND CONCLUSION

The present investigation fully achieved all the outlined objectives, offering a detailed and critical analysis of the role of nanostructured solutions applied to renewable energies in strengthening energy sustainability. Throughout the research, it was possible to consistently identify how these innovations contribute to promoting energy efficiency, expanding technological accessibility in vulnerable contexts, and mitigating the effects of climate change, in alignment with the Sustainable Development Goals established by the United Nations.

Regarding the first axis of the theoretical framework, it was observed that advances in materials and devices enabled by nanotechnology have significantly enhanced the efficiency of energy generation and storage systems. As evidence, the development of solar panels composed of nanomaterial layers stands out, which improves solar radiation absorption and photovoltaic conversion, thereby reducing energy losses and increasing device longevity. This technological progress represents a tangible step toward more efficient and sustainable energy alternatives.

In the second axis, related to energy accessibility, it was found that nanostructured technologies hold significant potential for democratizing access to clean energy sources. The study revealed that initiatives based on low-cost energy generation devices made from nanostructured materials have been successfully implemented in socially vulnerable communities, contributing to the fight against energy poverty. These actions not only enable access to energy but also promote social inclusion, local development, and improved quality of life, demonstrating that nanotechnology can be a key ally in reducing inequalities.

Lastly, in the third axis, it was demonstrated that nanotechnological solutions play a strategic role in the energy transition and in the decarbonization of the global energy matrix. The reviewed research indicates the use of nanomaterials in carbon capture, storage, and reuse processes, as well as in the production of less polluting alternative fuels such as green hydrogen. These contributions underscore the relevance of nanotechnology as a tool to combat climate change.

In light of the results obtained, it is suggested that future studies examine the techno-economic feasibility of large-scale implementation of these technologies, as well as the socio-environmental impacts resulting from their dissemination, aiming to ensure that innovation progresses in an ethical, safe, and inclusive manner.

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