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POWERSHORING, INNOVATION AND DECARBONIZATION: THE EMERGENCE OF GREEN INDUSTRIAL CHAINS IN BRAZIL'S NEW INDUSTRIAL GEOGRAPHY

POWERSHORING, INOVAÇÃO E DESCARBONIZAÇÃO: A EMERGÊNCIA DAS CADEIAS INDUSTRIAIS VERDES NA NOVA GEOGRAFIA INDUSTRIAL DO BRASIL

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ABSTRACT

The transition toward a low-carbon economy has been reshaping industrial location strategies and production chains, increasing the relevance of renewable energy availability, innovation, and decarbonization to industrial competitiveness. In this context, *powershoring* emerges as a dimension associated with the territorial reorganization of production and the emergence of green industrial chains in Brazil. The general objective is to analyze how *powershoring*, innovation, and decarbonization contribute to the emergence of green industrial chains within Brazil's new industrial geography. The research is qualitative and was conducted through a literature review and documentary research, which made it possible to connect scientific production with evidence found in institutional and technical documents addressing *powershoring*, innovation, renewable energy, and industrial decarbonization. This approach enabled the integration of different analytical perspectives and the compilation of the theoretical and documentary elements necessary to understand the relationships among energy, innovation, sustainability, competitiveness, and the reorganization of industrial activities in the Brazilian context. The results indicate that *powershoring* can influence new industrial location decisions in territories endowed with renewable energy resources and adequate infrastructure, while technological and organizational innovation contributes to transforming these conditions into productive capabilities, efficiency, and value creation. The findings also indicate that decarbonization requires coordination among energy efficiency, renewable energy, innovation, industrial policy instruments, and institutional coordination, potentially contributing to sustainable competitiveness and strengthening green industrial chains. The integration of these dimensions indicates that the energy transition can extend beyond the replacement of energy sources and

contribute to the reorganization of production systems and the repositioning of Brazilian industry within global value chains.
Keywords: *Powershoring*. Innovation. Decarbonization. Green industrial chains.

RESUMO

A transição para uma economia de baixo carbono vem reconfigurando as estratégias de localização industrial e as cadeias produtivas, ampliando a relevância da disponibilidade de energias renováveis, da inovação e da descarbonização para a competitividade industrial. Nesse contexto, o powershoring apresenta-se como uma dimensão associada à reorganização territorial da produção e à emergência de cadeias industriais verdes no Brasil. O objetivo geral consiste em analisar como o powershoring, a inovação e a descarbonização contribuem para a emergência das cadeias industriais verdes na nova geografia industrial do Brasil. A pesquisa caracteriza-se como qualitativa, desenvolvida mediante revisão bibliográfica e pesquisa documental, procedimentos que possibilitaram articular a produção científica às evidências presentes em documentos institucionais e técnicos sobre powershoring, inovação, energias renováveis e descarbonização industrial. Essa abordagem permitiu integrar diferentes perspectivas analíticas e reunir elementos teóricos e documentais necessários à compreensão das relações entre energia, inovação, sustentabilidade, competitividade e reorganização das atividades industriais no contexto brasileiro. Os resultados evidenciaram que o powershoring pode favorecer novas decisões de localização industrial em territórios dotados de recursos energéticos renováveis e infraestrutura adequada, enquanto a inovação tecnológica e organizacional contribui para converter essas condições em capacidades produtivas, eficiência e agregação de valor. Verificou-se,

ainda, que a descarbonização requer articulação entre eficiência energética, energias renováveis, inovação, instrumentos de política industrial e coordenação institucional, podendo contribuir para a competitividade sustentável e para o fortalecimento das cadeias industriais verdes. A integração dessas dimensões indica que a transição energética pode ultrapassar a substituição de fontes de energia e participar da reorganização dos sistemas produtivos e do reposicionamento da indústria brasileira nas cadeias globais de valor.
Palavras-chave: Powershoring; Inovação; Descarbonização; Cadeias industriais verdes.

1. INTRODUCTION

The transition toward a low-carbon economy is reshaping industrial location strategies, global value chains, and the parameters of competitiveness. The intersection of renewable energy availability, technological innovation, and industrial decarbonization is opening pathways for the geographical reorganization of production and the development of green industrial chains. In Brazil, this dynamic is particularly relevant due to the abundance of renewable energy sources, the diversity of its territory, and the need to increase industrial value creation by combining environmental benefits, technological capabilities, and solid competitiveness in both domestic and international markets. In this context, *powershoring* emerges as an approach to industrial location in areas with access to renewable energy, while innovation, combined with decarbonization, transforms these conditions into productive capabilities suited to the requirements of a low-carbon economy.

Against this backdrop, the present study addresses the following research problem: How do *powershoring*, innovation, and decarbonization contribute to the emergence and strengthening of green industrial chains within Brazil's new industrial geography? To address this question, the general objective is to analyze how *powershoring*, innovation, and decarbonization contribute to the emergence of green industrial chains within Brazil's new industrial geography. The specific objectives are to: understand the foundations of *powershoring* and its relationship with the reconfiguration of production chains and contemporary industrial geography; analyze the role of technological and organizational innovation in consolidating green and sustainable industrial chains; and examine industrial decarbonization strategies and their contributions to strengthening the competitiveness and sustainability of Brazilian industry.

The research is qualitative and was conducted through a literature review and documentary research. These procedures made it possible to connect scientific production with evidence found in institutional and technical documents addressing *powershoring*, innovation, renewable energy, and industrial decarbonization. This approach enabled the integration of different analytical perspectives and the compilation of the theoretical and documentary elements necessary to understand the relationships among energy, innovation, sustainability, competitiveness, and the reorganization of industrial activities in the Brazilian context.

The article is organized into four sections. The first presents the Introduction, in which the topic, research problem, general objective, and specific objectives are contextualized. The second corresponds to the Methodology, which describes the research approach and procedures employed. The third presents the Theoretical Framework, structured into three topics addressing *powershoring* and the new industrial geography, innovation and green industrial chains, and industrial decarbonization and sustainable competitiveness. Finally, the fourth section presents the Final Considerations, which summarize the main findings of the analysis and indicate possibilities for future research.

2. THEORETICAL FRAMEWORK

This theoretical framework was organized into three interconnected topics that structure the analysis of the relationship among energy, innovation, and decarbonization in the emergence of green industrial chains in Brazil. The first topic addresses *powershoring* and its relationship with the new industrial geography and the reconfiguration of production chains; the second examines innovation and the technological capabilities associated with the development of green industrial chains; and the third analyzes industrial decarbonization, considering its challenges, strategies, and contributions to the sustainable competitiveness of Brazilian industry.

2.1. Powershoring And The New Industrial Geography: Transformations In Production Chains And Opportunities For Brazil

The reconfiguration of global value chains is one of the most significant changes in the international economy in recent decades. Geopolitical instability, climate change, regulatory demands concerning carbon emissions, and concerns about energy security have reduced the relevance of production models based solely on minimizing production costs. As a result, globalization, regionalization, and reindustrialization are occurring simultaneously, as companies increasingly reassess where to locate their production facilities based on criteria such as resilience, logistics reliability, and access to low-carbon energy. This dynamic is encouraging new forms of industrial organization, including *nearshoring*, *friendshoring*, *reshoring*, and, more recently, *powershoring*, which places greater emphasis on renewable energy infrastructure in investment decisions (Arbache; Esteves, 2023; Araújo et al., 2025).

Although all these approaches seek to reduce vulnerabilities in production chains, they are based on different principles. *Nearshoring* focuses on geographical proximity between production and consumption, thereby reducing costs and delivery times. *Friendshoring*, in turn, favors trade relations with countries regarded as strategic allies and politically stable, with the aim of ensuring greater institutional predictability. *Reshoring* refers to the return of industrial operations that had previously been transferred to other countries, whereas *powershoring* goes a step further by incorporating a new locational factor, linking industrial competitiveness to the availability of abundant, reliable, and economically attractive renewable energy.

According to Schneider, Santos and Arbache Filho (2026, p. 101),

> *In this context, the concept of powershoring emerges as an appropriate strategy for catalyzing this transformation by proposing the attraction of energy-intensive industries to areas close to abundant and low-cost renewable energy sources, optimizing the value chain, reducing risks and emissions, and transforming comparative advantage into competitive advantage for the Region. Powershoring would represent an advanced expression of the Region's contribution to the thesis of industrialization based on comparative advantages.*

This perspective demonstrates that contemporary industrial competitiveness increasingly depends on the integration of energy infrastructure, technological innovation, and territorial planning (Schneider; Santos; Arbache Filho, 2026).

Powershoring emerges as a direct consequence of advances in the global energy transition. As electricity-intensive sectors, such as steelmaking, metallurgy, fertilizer production, low-carbon hydrogen, ammonia, and synthetic fuels, strengthen their decarbonization commitments, the origin of the energy used in production becomes an increasingly decisive factor in international competitiveness. According to reports from the International Energy Agency, the growing adoption of renewable energy sources is one of the main drivers of industrial transformation in the coming decades, benefiting countries capable of combining a high share of clean energy with adequate logistics infrastructure and an investment-friendly environment (IEA, 2024a; IEA, 2024b; IEA, 2024c). In addition, the International Renewable Energy Agency indicates that the electrification of industrial processes and the use of low-carbon hydrogen are expected to reshape production chains worldwide, increasing the relevance of areas with abundant renewable resources (IRENA, 2023).

Within this context, Brazil possesses attributes that strengthen its position in the new industrial geography driven by the energy transition. The high share of renewable sources in the electricity mix, combined with abundant wind and solar resources, creates favorable conditions for attracting energy-intensive industries committed to climate neutrality goals. The regional diversity of natural resources also enables the emergence of new industrial hubs connected to low-carbon economy value chains, reinforcing the relationship among renewable generation, port infrastructure, technological innovation, and industrial value creation.

As emphasized by the International Energy Agency (2024, p. 11),

> *Brazil is well positioned to produce and export green steel, aluminum, and low-carbon ammonia by taking advantage of its renewable electricity mix. It also highlights that the country could increase its exports of wind energy components sixfold by 2035 if it invests in logistics and port infrastructure.*

The report further states that:

> *Powershoring is a notable and promising example of this new strategy. The Region can export energy, but embedded in industrial products. Powershoring, therefore, represents a promising shortcut for the Region to advance its industrialization by aligning the global energy transition with its own economic development (IEA, 2024, p. 11).*

This dynamic is already beginning to materialize in initiatives aimed at creating green industrial chains in Northeastern Brazil. The development of low-carbon hydrogen in the Pecém Industrial and Port Complex, in Ceará, and in the Suape Industrial Port Complex, in Pernambuco, demonstrates how renewable energy, combined with port infrastructure and proximity to international markets, is beginning to shape decisions regarding where industries should be located (Governo do Ceará, 2025; Governo de Pernambuco, 2025). Along these lines, Araújo et al. (2025) argue that *powershoring* can be understood as a regional development strategy that strengthens Northeastern Brazil's competitiveness in global value chains, while Arbache and Esteves (2023) indicate that it can contribute to reducing carbon emissions, increasing energy security, and diversifying Latin America's industrial base. In this sense, the intersection of innovation, renewable energy, and industrial policies creates a new logic of production location, in which competitiveness is shaped by the ability to combine sustainability, technology, and higher value-added production.

The consolidation of *powershoring* in Brazil, however, requires coordination among industrial policies, energy planning, and the strengthening of innovation ecosystems. Electricity generated from renewable sources represents a competitive advantage, but translating this advantage into industrial development requires investment in logistics infrastructure, increased transmission capacity, the training of qualified professionals, and a stable regulatory environment. From this perspective, innovation is no longer merely a factor driving productivity and becomes fundamental to the formation of production chains capable of integrating low-carbon technologies, increasing value creation, and expanding the international presence of Brazilian industry. This interpretation is consistent with the analyses of Arbache and Esteves (2023), which demonstrate that industrialization driven by *powershoring* depends on the articulation of energy security, technological innovation, and industrial competitiveness.

In the Brazilian context, this process is expected to result in a spatial reconfiguration of industrial activity, benefiting areas with abundant renewable energy and infrastructure aligned with international markets. Northeastern Brazil stands out in this context because it combines complementary wind and solar resources, abundant areas for new projects, and the strategic location of its port complexes. What can be observed in the Pecém Complex, in Ceará, and the Suape Industrial Port Complex, in Pernambuco, is that projects associated with low-carbon hydrogen can act as catalysts for the emergence of new production chains, encouraging investments in areas such as green steel, fertilizers, sustainable fuels, and the production of renewable energy equipment (Governo do Ceará, 2025; Governo de Pernambuco, 2025). As Araújo et al. (2025) point out, this restructuring can foster regional development by integrating energy infrastructure, industrial production, and competitiveness in global value chains.

Although this scenario is promising, its realization depends on overcoming challenges related to institutional coordination and long-term planning capacity. Growing demand for critical minerals, industrial electrification, and low-carbon fuels is increasing international competition for productive investment, making it essential for public policies to reduce regulatory uncertainties and foster innovation in the private sector. According to the International Energy Agency and the International Renewable Energy Agency, countries capable of combining renewable generation, infrastructure, technological innovation, and higher value-added industrial chains will be better positioned to develop a more competitive low-carbon economy (IEA, 2024a; IEA, 2024b; IEA, 2024c; IRENA, 2023). Thus, *powershoring* should not be viewed solely as a location strategy, but as an industrial development model that responds to the structural changes associated with the energy transition. The following Table 1 summarizes the reorganization of production chains and their relationship with *powershoring*.

Table 1. Strategies for reorganizing production chains and their relationship with *powershoring*

Strategy	Main characteristics	Predominant location criterion	Contribution to decarbonization	Relevance to Brazil
Nearshoring	Transfer of production to geographically closer countries and closer to the	Geographical proximity and reduction of logistics costs.	Indirect, by reducing transportation distances.	Fosters regional integration and trade in the Americas.

	consumer market.			
Friendshoring	Relocation of production among countries considered strategic and institutionally reliable partners.	Political stability, economic security, and international cooperation.	Moderate, depending on the energy mix of the countries involved.	Expands commercial opportunities within strategic industrial chains.
Reshoring	Return of productive activities to the company's country of origin.	Strengthening of domestic industry, reduction of external dependence, and increased productive resilience.	Variable, depending on the national energy profile.	Encourages reindustrialization and reduces vulnerabilities in production chains.
Powershoring	Establishment of energy-intensive industries near regions with high availability of renewable energy sources.	Competitive renewable energy supply, infrastructure, and logistics capacity.	High, due to the reduction of emissions associated with production processes.	Favors the production of low-carbon hydrogen, green steel, low-carbon ammonia, sustainable fuels, and other segments of green industry.

Source: Prepared by the authors based on Arbache and Esteves (2023), IRENA (2023), IEA (2024a, 2024b, 2024c), Araújo et al. (2025), Governo do Ceará (2025), Governo de Pernambuco (2025), and Schneider, Santos and Arbache Filho (2026).

Thus, it is possible to observe that green industrial chains emerge from the convergence of economic, technological, energy, and environmental changes that are reshaping the current industrial geography. *Powershoring* encapsulates this new paradigm by linking the availability of renewable energy to the capacity to attract electricity-intensive industrial investments, thereby promoting competitiveness, decarbonization, and regional development. The combination of a renewable electricity mix, port infrastructure, and natural resources, together with Brazil's efforts to develop low-carbon hydrogen, particularly in the Northeast, favors the country's greater participation in the global value chains of the low-carbon economy. Understanding the principles of *powershoring*, therefore, helps clarify the changes underway in the new industrial geography and provides an analytical framework for discussing the interaction among innovation, sustainability, and reindustrialization in Brazil.

2.2. Innovation And Green Industrial Chains: Technological Capabilities For Sustainable Development

The consolidation of green industrial chains depends, to a large extent, on the ability of production systems to integrate technological, organizational, and institutional innovations into their transformation processes. In the transition toward a low-carbon economy, innovation goes beyond the development of new products, encompassing changes aimed at minimizing environmental impacts, increasing the efficiency of natural resource use, and fostering new models of production and consumption. This definition is consistent with the Oslo Manual, which characterizes innovation as “a new or improved product or process (or combination thereof) that differs significantly from the unit’s previous products or processes and that has been made available to potential users (product) or brought into use by the unit (process)” (OCDE; EUROSTAT, 2018, p. 68). From this perspective, innovation becomes a fundamental driver of industrial competitiveness and of the development of production chains aligned with the challenges of decarbonization, as it promotes productivity, technological differentiation, and adaptation to new regulatory and market demands (Rodrigues, 2019).

The integration of sustainability into innovation processes has intensified discussions around concepts such as sustainable innovation, eco-innovation, and green innovation. Although these approaches have distinct conceptual features, they converge on the understanding that technological advancement should simultaneously generate economic, environmental, and social benefits. For Barbieri (2024), the transition from traditional innovation to eco-innovation represents a genuine milestone, as reducing environmental impacts ceases to be a by-product of productive activity and becomes a driving force behind technological development. Similarly, Pinsky and Kruglianskas (2017) argue that successful business experiences demonstrate that innovation strategies for sustainability enhance organizational competitiveness by integrating productive efficiency, environmental management, and adaptation to technological innovations. Consequently, environmental innovation becomes an essential element for industrial chains seeking to reconcile economic growth with environmental responsibility and competitiveness in markets increasingly guided by sustainability standards.

This shift is driven by the widespread adoption of digital technologies and the consolidation of Industry 4.0 principles, which are establishing new patterns of industrial production organization. The combination of artificial intelligence, the Internet of Things, big data, process automation, cloud computing, and cyber-physical systems enables more precise production control, reduces waste, improves energy consumption management, and increases operational efficiency. In this context, digital transformation can act as a catalyst for the adoption of clean technologies, supporting industrial models that are both economically and environmentally more efficient. According to Largura and Valadares (2024), the adoption of green technologies simultaneously strengthens the environmental performance and competitiveness of organizations, particularly when aligned with continuous innovation strategies. Gupta (2019) argues that the dissemination of environmental technologies is one of the main means of reducing emissions, improving the efficiency of natural resource use, and facilitating the transition toward production systems aligned with sustainable development goals.

For green industrial chains to become consolidated, it is essential to strengthen research, development, and innovation (R&D&I) activities and promote greater interaction among companies, universities, research centers, and public institutions. Structuring innovation ecosystems facilitates the flow of information, technological cooperation, and the development of skills that can accelerate the adoption of new production processes with lower environmental impacts. In this sense, green innovation is an organizational attribute that is continuously developed through technological learning, knowledge management, and the adoption of sustainable practices. In a study of food industries, Ramos (2025) argues that the improvement of this capability results from the interaction among innovation, environmental management, and technological development. From a complementary perspective, Vieira and Camargo emphasize that green dynamic capabilities increase organizations' readiness to adapt to changes in the competitive environment, thereby fostering the creation of green innovations and the strengthening of sustainable competitive advantages (Vieira; Camargo, 2024).

This dynamic is supported by Montenegro (2022, p. 267), who argues that:

> *when the green economy is considered as a process, importance is placed on a continuous process involving the gradual transformation of production and consumption patterns toward more sustainable and less polluting practices. The implementation of sustainable practices may take time and involve technical and economic challenges, but it is an important process for ensuring the health of the planet and future generations.*

This understanding reinforces the idea that the formation of green industrial chains depends on a continuous process of innovation, learning, and technological adaptation, guided by sustainability objectives and long-term economic development.

Intellectual property protection plays a fundamental role in consolidating green innovation by providing instruments that support the secure disclosure and appropriation of knowledge. It not only ensures that innovations are appropriately shared and managed, but also encourages investment in research, development, and innovation. In this way, it becomes indispensable for advancing technologies that promote sustainability and for developing new solutions within an increasingly complex environmental context. Intellectual property protection instruments, such as patents, utility models, software registration, and technology transfer agreements, are essential for transforming the outcomes of scientific research into innovations that can be incorporated into production processes. This transformation is fundamental because it not only facilitates the adoption of innovations but also significantly increases the competitiveness of industrial chains committed to sustainability and environmental responsibility. Thus, the use of these strategic instruments strengthens industries oriented toward the green economy. However, the specialized literature makes clear that understanding intellectual property also means understanding a much broader innovation ecosystem. At this point, collaboration among different actors, including universities, companies, research centers, and government institutions, becomes essential, since such interaction enables and fosters the continuous generation of environmentally responsible technologies (OCDE; EUROSTAT, 2018; Rodrigues, 2019).

From this perspective, protecting knowledge is not limited to the financial appropriation of emerging innovations; it is also crucial for expanding the capacity to share technologies and for creating productive environments oriented toward sustainable development. Clearly, both respect for and preservation of knowledge are fundamental not only for immediate returns but also for the growth and sustainability of the productive ecosystem as a whole.

The consolidation of green industrial chains also depends on the adoption of clean technologies that increase production efficiency and reduce the intensity of natural resource use. This process encompasses, among other measures, the upgrading and modernization of outdated equipment, as well as the electrification of industrial processes. In addition, energy consumption is optimized so that resources can be used more efficiently. The valorization of waste, understood as the conversion of by-products into reusable resources, is another important aspect, as it contributes to the development of a circular economy. Finally, the adoption of intelligent environmental monitoring systems is also crucial because it enables more effective monitoring of environmental conditions.

According to Barbieri (2024), eco-innovation radically transforms traditional production practices by aligning economic performance with environmental commitment from the earliest stages of technological solution design. This new perspective emphasizes the need to integrate environmental considerations into all stages of the innovation process, thereby transforming the way companies develop their technologies.

From this interpretive perspective, Gupta (2019) emphasizes that green technologies are important tools for reducing pollutant emissions, managing waste, and maximizing the efficiency of production systems. Furthermore, Pinsky and Kruglianskas (2017) indicate that organizations committed to innovation tend to achieve more positive results when they continuously integrate sustainability into their corporate strategies rather than merely responding to regulatory requirements.

International experience shows that countries and regions that have established strong innovation policies, research funding mechanisms, and technological ecosystems have been able to accelerate the development of industrial chains linked to the low-carbon economy. Despite differences among institutional models, several common elements can be identified, including incentives for applied research, university-industry cooperation, financing for clean technologies, intellectual property protection, and support for the digital transformation of industry. These elements foster innovative environments capable of increasing industrial competitiveness while maintaining environmental objectives.

As Montenegro (2022) argues, the green economy should not be understood as a final destination, but rather as a continuous process of transforming production and consumption patterns that requires gradual changes, institutional coordination, and ongoing technological learning. This indicates that the consolidation of green industrial chains results from the synergy among innovation, sustainability, and long-term strategic planning. Table 2, presented below, summarizes the main elements discussed in this section, highlighting how different dimensions of innovation contribute to the formation and consolidation of green industrial chains and to sustainable development.

Table 2. Dimensions of innovation and their contributions to the consolidation of green industrial chains

Dimension	Characteristics	Contributions to green industrial chains
Sustainable innovation	Development of products, processes, services, and organizational models	Promotes competitiveness, reduces environmental

	aligned with the principles of sustainability.	impacts, and generates socioeconomic value.
Eco-innovation and green innovation	Development of technological solutions aimed at reducing emissions, efficient use of resources, and pollution prevention.	Promotes low-carbon production, productive efficiency, and strengthening of the green economy.
Industry 4.0 and digital transformation	Integration of artificial intelligence, the Internet of Things, automation, data analysis, and intelligent systems into productive processes.	Expands productivity, reduces waste, improves environmental monitoring, and optimizes energy consumption.
Research, Development, and Innovation (R&D&I)	Systematic production of scientific and technological knowledge applied to industrial demands.	Generates clean technologies, accelerates innovation, and strengthens industrial competitiveness.
Innovation ecosystems	Cooperation among universities, companies, governments, and research centers.	Favors technology transfer, collaborative learning, and the development of sustainable solutions.
Intellectual property	Legal protection of innovations through patents, registrations, and other legal instruments.	Stimulates investment in innovation, technology transfer, and the secure dissemination of knowledge.
Green dynamic capabilities	Organizational competencies to continuously adapt processes, technologies, and strategies to environmental demands.	Strengthens green innovation, business resilience, and sustainable competitiveness.

Source: Elaborado pelo autor com base em OCDE e Eurostat (2018), Rodrigues (2019), Gupta (2019), Montenegro (2022), Largura e Valadares (2024), Barbieri (2024), Ramos (2025), Pinsky e Kruglianskas (2017) e Vieira e Camargo (2024).

It is, therefore, through technological and organizational innovation that one of the central factors in the formation and consolidation of green industrial chains can be understood. The articulation among R&D&I, digital transformation, clean technologies, dynamic capabilities, intellectual property protection, and collaboration among the different actors within innovation ecosystems enhances opportunities for creating more efficient and sustainable production processes.

It is in this context that innovation should not be understood merely as a driver of business competitiveness, but as a structuring factor in the transition toward a low-carbon economy. Therefore, strengthening green industrial chains requires the articulation of scientific knowledge, technological development, and sustainability through strategies that promote economic growth, industrial innovation, and the reduction of environmental impacts in an integrated manner.

2.3. Industrial Decarbonization And Sustainable Competitiveness: Challenges And Prospects For Green Industrial Chains In Brazil

Industrial decarbonization is part of a profound transformation of production systems, driven by the urgent need to reduce greenhouse gas emissions while keeping the climate agenda connected to economic development and competitiveness goals. The energy transition is gradually changing the parameters that shape investment decisions, the location of industrial activities, and the organization of production chains. Reducing carbon intensity is no longer limited to simply replacing energy sources; it also involves energy efficiency, technological innovation, changes in production processes, waste management, the circular economy, and new forms of interaction between suppliers and companies. CNI (2023) understands decarbonization as an agenda that can create both risks and opportunities for Brazilian industry and, therefore, emphasizes the importance of a coordinated strategy that brings together climate policies, economic instruments, and competitiveness.

Carbon neutrality and Net Zero targets have, in this context, become important references for transforming industrial systems. Achieving them, however, requires climate commitments to be translated into organizational and technological changes that can be effectively implemented and verified. Decarbonization can be pursued through different strategies, including energy efficiency, process electrification, the use of renewable energy sources, the replacement of carbon-intensive inputs, the energy recovery of waste and, in some sectors, the use of low-carbon hydrogen and other technologies aimed at reducing emissions (CNI, 2023).

With regard to Brazilian industry, this transition has an important particularity: the country's electricity matrix, which has a high share of renewable sources, facilitates the reduction of emissions associated with electricity consumption. However, this does not eliminate the challenges faced by sectors in which emissions result from industrial processes themselves or from the use of fuels and raw materials. According to CNI (2023), Brazil's energy transition is closely related to productivity gains, innovation, and access to new markets, highlighting the connection between environmental performance and industrial competitiveness.

The economic dimension of decarbonization becomes particularly relevant when considering the adoption of carbon-pricing mechanisms. The introduction of such instruments can change cost structures, investment patterns, and business decisions, producing different effects across sectors and economic groups.

Santos (2018) draws attention to the need to assess the competitiveness risks and distributional impacts associated with implementing carbon-pricing instruments in Brazilian industry.

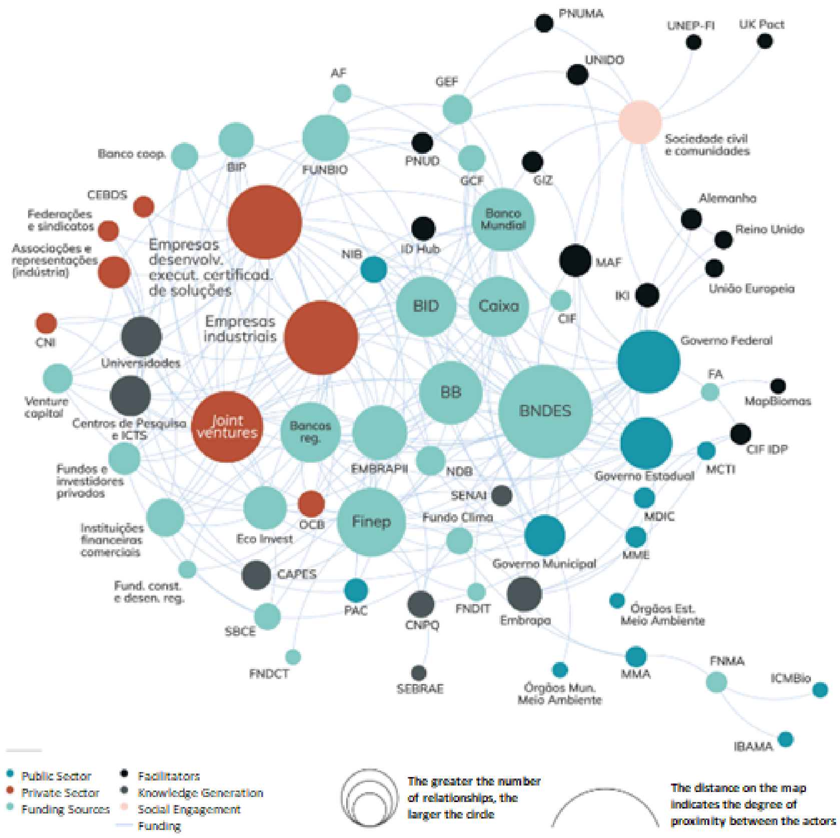
From a complementary perspective, Wills et al. (2021) analyze the economic and social effectiveness of different carbon-pricing schemes in achieving Brazil's climate targets, showing that the design of policy instruments can influence both environmental outcomes and their economic effects.

The issue, therefore, is not simply a matter of establishing a price for emissions. It also involves building mechanisms capable of encouraging changes in production without creating inequalities that could weaken the participation of Brazilian industrial sectors in international markets (Wills et al., 2021).

The financing structure is another important element in the capacity to implement decarbonization strategies. Investments in energy efficiency, electrification, renewable energy sources, process innovation, the circular economy, and lower-emission technologies require financial resources, technical knowledge, and institutional mechanisms capable of reducing the risks associated with changes in production.

The relational map presented below (Figure 1) illustrates the diversity of actors involved in Brazil's industrial decarbonization ecosystem, bringing together public institutions, banks, funds, companies, universities, research centers, civil society organizations, and international organizations. This representation helps to show that the transition toward green industrial chains does not take place exclusively within companies. Rather, it depends on networks of financing, knowledge, regulation, and cooperation.

Figure 1 – Mapping Brazil's industrial decarbonization ecosystem: financing relationships



Source: Gonçalves (2026)

Wilkinson (2025) demonstrates that the challenges of decarbonization also need to be analyzed in light of the specific characteristics of production chains. In the beef agro-food chain, for example, reducing emissions involves issues that go beyond the boundaries of industrial facilities and extend to primary production, traceability, land use, relationships between suppliers and slaughterhouses, and the demands of consumer markets. This perspective is particularly relevant for understanding decarbonization as a systemic process in which different links in the chain need to develop mechanisms for coordination and monitoring.

The following Table 3 contributes to this perspective by relating the production structure of livestock farming and slaughterhouses to mechanisms of regulation, monitoring, international pressure, and traceability. Thus, sustainable competitiveness does not depend solely on a company's ability to reduce its own emissions, but also on its ability to demonstrate the origin, compliance, and environmental performance of products throughout the chain.

Table 3. Production structure and challenges related to decarbonization and deforestation

Source: Wilkinson (2025)

The relationship between decarbonization and competitiveness is also reflected in organizations' ability to transform environmental requirements into production and market strategies. Duarte and Harpia (2024, p. 2) observe that:

> *Companies are operating in a competitive environment in which the development of strategies becomes important as a way of creating differentiation from competitors. All business actions aimed at the process of attracting and retaining customers have become increasingly important and a critical success factor for organizations. Practices associated with the green economy contribute to the creation of competitive advantages by focusing on reducing environmental risks and preventing ecological degradation in pursuit of sustainable development.*

In this context, decarbonization can become a valuable strategy by responding simultaneously to environmental demands, changing market preferences, and the conditions for accessing certain trade flows. According to Assumpção and Campos (2018), when addressing green supply chain management, it is essential to integrate environmental criteria into relationships among suppliers, production processes, and distribution so that sustainability is understood beyond organizational boundaries.

The effectiveness of this transformation, however, depends on coordination among public policies, business strategies, financial instruments, and technological capabilities. Rocha and Silva (2025, p. 27) draw attention to this aspect by stating that:

> *The sectoral analyses developed demonstrate that, although Brazil has a predominantly renewable electricity matrix, abundant biomass, biodiversity, and a vast agricultural territory, these structural advantages may be wasted without effective strategic coordination. Decarbonization is a sectoral and structural challenge that requires profound and coordinated technological, organizational, and institutional transformations and, crucially, will not occur through market action alone.*

The availability of renewable resources, by itself, does not lead to industrial decarbonization. Gonçalves (2026), when addressing the connection between decarbonization and the competitiveness of Brazilian industry, places this agenda within the context of the changes required to ensure that emissions reductions remain aligned with the preservation of companies' productive and competitive capacity.

From this perspective, decarbonization takes the form of a restructuring of Brazil's industrial chains, seeking to integrate energy efficiency, electrification, the use of renewable energy sources, low-emission hydrogen, the circular economy, innovation, and climate policy instruments, all with the aim of transforming production patterns. Sustainable competitiveness, therefore, results from the ability to bring these dimensions together through consistent business strategies and industrial policies, so that the climate transition is not viewed merely as a regulatory requirement. The current agenda of Brazilian industry already links decarbonization to innovation, energy efficiency, the circular economy, climate finance, and technology development, highlighting the urgency of coordinated action involving different instruments and stakeholders (CNI, 2023).

In this regard, strengthening green industrial chains depends on the ability to transform renewable energy resources, technological knowledge, and institutional arrangements into production processes that are less carbon-intensive and generate greater added value. Decarbonization thus becomes a fundamental component of Brazil's industrial competitiveness, connecting environmental sustainability, innovation, and participation in new global value chains.

3. METHODOLOGY

Research on powershoring, innovation, and decarbonization in the emergence of green industrial chains within Brazil's new industrial geography is situated in a context of transformation of production systems, marked by the energy transition, the adoption of low-carbon technologies, and the growing connection between industrial competitiveness and sustainability. Investigating this dynamic requires an approach capable of relating economic, technological, energy, environmental, and territorial dimensions, considering both the scientific concepts and debates that shape the field and the institutional documents that reflect contemporary policies, strategies, and trends. In this regard, qualitative scientific research is appropriate because it allows for a contextualized interpretation of phenomena and an understanding of the relationships among the different dimensions of a research subject. According to Creswell (2014), qualitative inquiry makes it possible to examine phenomena within their contexts, giving importance to meanings, interpretations, and processes, while Gil (2019) highlights its contribution to the systematic analysis of scientific problems whose understanding requires the integration of different sources and perspectives.

Regarding the methodological approach, this study is characterized as qualitative, a methodology widely used in contemporary scientific research to understand complex phenomena and social, institutional, technological, and economic processes that cannot be adequately examined solely through quantitative measurements. Within this investigation, the qualitative approach made it possible to critically interpret the relationships among energy availability, industrial location, innovation, decarbonization, and the reorganization of production chains, while preserving the complexity of these interactions. For Creswell (2014), qualitative research enables the construction of well-grounded interpretations based on the analysis of different sources and perspectives, whereas Gil (2019) emphasizes its relevance to studies aimed at understanding phenomena within their contexts. Thus, this approach made it possible to examine the research subject beyond the isolated identification of variables, taking into account its economic, technological, environmental, and institutional dimensions.

Two research procedures were used to develop the study: a bibliographic review and documentary research, employed in a complementary manner. The bibliographic review was based on the analysis of theses, monographs, scientific articles published in academic journals, books, and specialized blogs, making it possible to bring together concepts, interpretations, and research findings related to powershoring, innovation, renewable energy, decarbonization, and green industrial chains. This procedure provided the theoretical and conceptual foundation for the investigation, helped identify different perspectives on the research subject, and supported the construction of the analytical relationships developed throughout the study. According to Gil (2019), bibliographic research is an important procedure for systematizing previously produced scientific knowledge, contributing to the theoretical foundation and delimitation of the research problem.

Documentary research, in turn, focused on the analysis of institutional and technical documents selected because of their relevance to understanding the energy, technological, and industrial transformations related to the research subject. The documents analyzed were: the Green Hydrogen Hub of the Pecém Industrial and Port Complex, from the Government of Ceará (2025); the Green Hydrogen Strategy of Suape, from the Government of Pernambuco; the *World Energy Outlook 2024*, *Renewables 2024*, and *Energy Technology Perspectives 2024*, published by the International Energy Agency (IEA, 2024); the *World Energy Transitions Outlook 2023*, published by the International Renewable Energy Agency (IRENA, 2023); and the *Oslo Manual 2018*, prepared by the Organisation for Economic Co-operation and Development and Eurostat (OECD; EUROSTAT, 2018). The analysis of these documents made it possible to incorporate institutional information, guidelines, energy perspectives, innovation frameworks, and elements related to contemporary technological and industrial transformations into the study. Salge, Oliveira, and Silva (2021) emphasize that documentary research requires systematic procedures for selecting, organizing, and analyzing sources so that documents are examined in relation to the research problem and objectives.

The combined use of these two procedures was appropriate to the purposes of the research because it made it possible to bring established scientific knowledge closer to the evidence and guidelines found in institutional and technical documents. While the bibliographic review provided the conceptual foundations and academic interpretations necessary to understand powershoring, innovation, and decarbonization, the documentary research made it possible to examine documents directly related to policies, energy strategies, technologies, and institutional initiatives relevant to the context under investigation. This complementarity strengthened the analysis by allowing different types of sources to be brought into dialogue while preserving the qualitative approach and interpretive nature of the study. Thus, the combination of bibliographic review and documentary research proved consistent with the proposed research problem and objectives, contributing to an integrated understanding of the relationships among renewable energy, innovation, decarbonization, and the transformation of Brazil's industrial geography.

4. FINAL CONSIDERATIONS

The transition toward a low-carbon economy has been bringing significant changes to the spatial organization of production, industrial location criteria, and the relationships that structure global value chains. In this context, the connection between powershoring, innovation, and decarbonization becomes relevant for understanding the emergence of new industrial configurations in

Brazil, particularly in view of the availability of renewable energy sources, the need to reduce greenhouse gas emissions, and the growing incorporation of environmental criteria into investment decisions and trade flows. The research developed under the title “Powershoring, Innovation, and Decarbonization: The Emergence of Green Industrial Chains in Brazil's New Industrial Geography” proved relevant because it brings together energy, technological, environmental, economic, and territorial dimensions that, when considered jointly, help explain the conditions under which the energy transition can contribute to a new dynamic of Brazilian industrialization.

Considering the research problem, “How do powershoring, innovation, and decarbonization contribute to the emergence and strengthening of green industrial chains in Brazil's new industrial geography?”, the results of the analysis made it possible to address this question in an integrated manner. The findings indicate that powershoring introduces the availability of renewable energy as a relevant factor in industrial location decisions; innovation expands organizations' ability to develop and incorporate technologies, processes, and production models compatible with sustainability; and decarbonization guides the transformation of industrial systems toward lower emissions and greater efficiency in the use of resources. The interaction among these three elements contributes to changing traditional patterns of industrial location and production organization, favoring the formation of green industrial chains connected to the energy transition and the low-carbon economy.

The three specific objectives were achieved. The results showed that powershoring can influence industrial location decisions by linking the availability of renewable energy to territorial conditions and the reconfiguration of production chains; that technological and organizational innovation contributes to transforming these advantages into productive capabilities through R&D&I, clean technologies, digital transformation, knowledge management, intellectual property, and cooperation among different actors; and that industrial decarbonization requires integrated strategies involving energy efficiency, the expansion of renewable energy sources, electrification, low-carbon hydrogen, the circular economy, and climate policy instruments. These strategies contribute not only to reducing emissions, but also to competitiveness, market access, investment attraction, and the integration of Brazilian industry into global value chains.

In the first section of the theoretical framework, it became evident that the transformation of global value chains has been changing industrial location criteria, incorporating the availability of renewable energy as a relevant factor. In this context, powershoring connects energy, territory, and industry and may support the integration of Brazilian regions into segments associated with the energy transition, provided that it is accompanied by infrastructure, logistics, innovation, workforce development, and public policies.

In the second section of the theoretical framework, the findings showed that innovation represents a structural capability for the formation of green industrial chains through the incorporation of clean technologies, digital systems, automation, applied research, and new forms of production organization. In the third section, it was found that decarbonization requires coordinated technological, organizational, and institutional transformations involving energy efficiency, emissions reduction, financing, infrastructure, traceability, and public policies. Thus, powershoring, innovation, and decarbonization constitute interdependent dimensions in the transformation of Brazilian industrial systems.

The integration of the findings demonstrates that the energy transition can represent an opportunity for productive reorganization and for repositioning Brazilian industry within global value chains. Renewable energy can support the production of goods with lower carbon intensity, while innovation expands technological value creation and decarbonization strengthens the capacity to respond to the environmental requirements of markets. For this dynamic to effectively contribute to industrial development, it is necessary to connect energy resources, technological capabilities, infrastructure, financing, and public policies, with a focus on value addition and the consolidation of green industrial chains.

Regarding the continuity of the scientific research agenda, future investigations may further explore the interrelationships among powershoring, innovation, and decarbonization in different regional contexts, industrial sectors, and configurations of production chains in Brazil. Comparative studies across regions and economic sectors may shed light on the different pathways of industrialization associated with renewable energy supply, technological innovation, and reductions in carbon intensity. Further research may also examine productivity, value creation, qualified employment generation, climate finance, carbon pricing, intellectual property, and industrial policies. Such investigations can contribute to a deeper understanding of the factors that support the consolidation of green industrial chains and their integration into Brazil's new industrial geography.

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