THE ROLE OF THE TECHNOLOGICAL INNOVATION CENTER IN THE TRANSFER OF CLEANER TECHNOLOGIES IN THE FACE OF THE CARBON ADJUSTMENT MECHANISM AT THE EUROPEAN UNION BORDER

A ATUAÇÃO DO NÚCLEO DE INOVAÇÃO TECNOLÓGICA NA TRANSFERÊNCIA DE TECNOLOGIAS MAIS LIMPAS FRENTE AO MECANISMO DE AJUSTE DE CARBONO NA FRONTEIRA DA UNIÃO EUROPEIA

EL PAPEL DEL CENTRO DE INNOVACIÓN TECNOLÓGICA EN LA TRANSFERENCIA DE TECNOLOGÍAS MÁS LIMPIAS ANTE EL MECANISMO DE AJUSTE DE CARBONO EN LA FRONTERA DE LA UNIÓN EUROPEA

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ABSTRACT

This research aimed to analyze the role of Technological Innovation Centers (NITs), linked to Scientific, Technological and Innovation Institutions (ICTs), as drivers of cleaner technology development in the steel sector, considering the possibilities of technology transfer to adapt the sector to the requirements of the European Union Border Carbon Adjustment Mechanism (CBAM). The research has a qualitative approach, with bibliographic and documentary analyses on carbon emissions in the industrial sector, conventional technologies used in steelmaking, and cleaner technologies applicable to the steel sector. The results pointed to new routes for cleaner technologies for decarbonization and the importance of NITs in mediating between scientific production and the productive sector for the development of technologies in ICTs that can contribute to solving economic and environmental problems that help achieve global decarbonization goals and meet the requirements imposed by the CBAM. In conclusion, it can be said that there is a risk that Brazilian companies exporting steel products will lose competitiveness in the European market if strategies are not adopted to overcome the challenges imposed by carbon restriction policies on products that do not meet CBAM criteria.

Keywords: CBAM. Decarbonization. NIT.

RESUMO

Esta pesquisa teve como objetivo analisar o papel do Núcleo de Inovação Tecnológica (NIT), vinculados às Instituições Científicas, Tecnológicas e de Inovação (ICTs) enquanto indutor de desenvolvimento de tecnologias mais limpas no setor siderúrgico, considerando as possibilidades de transferência tecnológica para adequação do setor frente às exigências do

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Mecanismo de Ajuste de Carbono na Fronteira da União Europeia (CBAM). A pesquisa possui abordagem qualitativa, com análises bibliográficas e documentais sobre emissões de carbono no setor industrial, tecnologias convencionais utilizadas na siderurgia e tecnologias mais limpas aplicáveis ao setor siderúrgico. Os resultados apontaram novas rotas de tecnologias mais limpas para descarbonização e a importância dos NITs no intermédio entre produção científica e setor produtivo para o desenvolvimento de tecnologias, nas ICTs, que possam contribuir na resolução de problemas econômicos e ambientais que ajudem no alcance das metas globais de descarbonização e o atendimento às exigências impostas pelo CBAM. Por fim, pode-se concluir que há risco de as empresas brasileiras, exportadoras de produtos siderúrgicos, perderem competitividade no mercado europeu, caso estratégias não sejam adotadas para superar os desafios impostos pelas políticas de restrição de carbono sobre os produtos que não atenderem aos critérios do CBAM.

Palavras-chave: CBAM. Descarbonização. NIT.

RESUMEN
Esta investigación tuvo como objetivo analizar el papel de los Centros de Innovación Tecnológica (CNI), vinculados a las Instituciones Científicas, Tecnológicas y de Innovación (ICT), como impulsores del desarrollo de tecnologías más limpias en el sector siderúrgico, considerando las posibilidades de transferencia de tecnología para adaptar el sector a los requisitos del Mecanismo de Ajuste de Carbono en Frontera (CBAM) de la Unión Europea. La investigación tiene un enfoque cualitativo, con análisis bibliográficos y documentales sobre las emisiones de carbono en el sector industrial, las tecnologías convencionales utilizadas en la siderurgia y las tecnologías más limpias aplicables al sector siderúrgico. Los resultados apuntaron nuevas rutas para tecnologías más limpias para la descarbonización y la importancia de los CNI en la mediación entre la producción científica y el sector productivo para el desarrollo de tecnologías en TIC que puedan contribuir a la solución de problemas económicos y ambientales que ayuden a alcanzar las metas globales de descarbonización y a cumplir con los requisitos impuestos por el CBAM. En conclusión, se puede afirmar que existe el riesgo de que las empresas brasileñas exportadoras de productos siderúrgicos pierdan competitividad en el mercado europeo si no se adoptan estrategias para superar los desafíos que imponen las políticas de restricción de carbono a los productos que no cumplen con los criterios del CBAM.

Palabras clave: CBAM. Descarbonización. NIT.

1 INTRODUCTION

The growing search for sustainable development, given the environmental impacts resulting from greenhouse gas (GHG) emissions from industrial processes, brings light to the need for innovation in production processes for the transition to a low-carbon economy in view of the regulatory requirements imposed by the implementation of the European Union Carbon Border Adjustment Mechanism (CBAM/EU). The CBAM will affect important sectors of the world economy that are intensive in energy and GHG emissions, including the steel industry (APEXBRASIL, 2023), the focus of this research.

Brazil is one of the largest producers and exporters of steel in the world, and the steel production chain is essential for other sectors, such as civil construction, automotive, naval, machinery and equipment. As a major exporter to Europe, Brazil may face direct pressure to decarbonize its steel production, at the risk of losing competitiveness or paying high tariffs, which requires technological innovation, regulatory adjustments, and sustainability strategies to overcome this scenario (CNA, 2023).

The steel industry is one of the main sectors of the economy, as it provides important components for the infrastructure of the other sectors, by contributing turbines for wind energy generation or supports for solar panels, for example (FERNANDES et al., 2024). Despite its economic relevance, the industrial sector is intensive in energy consumption and greenhouse gas (GHG) emissions, being responsible for 2% of total emissions in the country in 2020 (FERNANDES et al., 2024), due to the use of fossil fuels as the main source of energy, making it one of the sectors with the greatest challenge to achieve decarbonization (IEA, 2022).

The predominant conventional technology in the steel industry consists of the use of fossil fuels as the main source of energy in the reduction of iron ore into steel, in Blast Furnace-Basic Oxygen Furnace (BF-BOF), a process that is intensive in both energy and CO2 emissions (IEA, 2020). The iron reduction stage is responsible for about 80% of GHG emissions in the crude steel production process, because the reducing agent and heat source used is mineral coal (FERNANDES et al., 2024), a non-renewable fuel.

In this context, Science, Technology and Innovation Institutions (ICT), through the Technological Innovation Centers (NITs), play a fundamental role in the generation of knowledge, production of new technologies and their effective transfer to the productive sector (LEITE; MENDONÇA; OLIVEIRA, 2023), which can help industries in the sector reduce their GHG emissions.

The NITs, formed by one or more ICTs, aim to manage the institutional innovation policy, in addition to bringing the academic and productive sectors closer together (QUEIROZ

et al., 2022). Such contributions were made possible by the creation of the Innovation Law, Federal Law No. 10,973/2004, which institutes measures to encourage innovation and scientific and technological research in the productive sphere (BRASIL, 2004), later updated by Federal Law No. 13,243, of January 11, 2016, known as the new Legal Framework for Science, Technology and Innovation, which improves measures to encourage innovation and research in the productive sphere, aiming at training and technological autonomy, and the productive development of the country (MCTIC, 2016).

In view of the above, this article aims to analyze the role of the Technological Innovation Center (NIT), linked to the Scientific, Technological and Innovation Institutions (ICTs) as an inducer of the development of cleaner technologies in the steel sector, considering the possibilities of technology transfer to adapt the sector to the requirements of the CBAM.

To achieve the proposed objective, an exploratory research was carried out, with a qualitative approach. Literature reviews on the subject were carried out on specialized search platforms

The research is justified by the environmental and economic impact that the Mechanism will have on Brazilian companies exporting steel products to the European Union. In addition, in order to meet the requirements established by the mechanism, with the need to reduce CO2 emissions, it is necessary to implement cleaner technologies, which, according to Silva Júnior and Andrade (2011), require greater investment in research, development and innovation, ratifying the theoretical relevance of this research.

The research is also justified by its theoretical and practical relevance, with the generation of structured knowledge about the technologies used in the steel industry, which will allow the Technological Innovation Centers (NITs) and Brazilian companies to anticipate trends, establish strategic partnerships and incorporate sustainable innovations to meet CBAM regulations.

In research carried out on the subject, no products were identified, until the closing of the present investigation, that present the role of NITs for the industrial adaptation of the Brazilian steel sector in the face of the requirements of the Carbon Adjustment Mechanism at the Border of the European Union (CBAM), with emphasis on the development of cleaner technologies and technology transfer. Mediating scientific production and the productive sector

2 THEORETICAL FRAMEWORK

Cleaner technologies play a fundamental role, given that they act preventively,

reducing Greenhouse Gas (GHG) emissions, among other benefits, such as reducing the production of solid waste in the initial process of steel and iron production. According to Law 12.305/2010, which institutes the National Solid Waste Policy, solid waste is materials, substances or objects discarded in its solid state, originating from human activity (BRASIL, 2010)

For Cumming, Henriques and Sadorsky (2016), clean technologies are processes that aim at less waste generation in production, including the generation of biomass and recycling processes, while Silva Júnior and Andrade (2011) state that the technologies proposed to treat the waste generated, that is, to treat the consequences and not act in a preventive way to environmental impacts, will tend to be classified as end-of-pipe technologies.

Cleaner technologies put nations on the path to transition to a low-carbon economy. In addition, it can reduce the costs of decarbonization, considering that there is a tendency to create restrictive carbon policies, as has already been happening with the European Union (EU).

In 2023, the EU created the Carbon Border Adjustment Mechanism (CBAM), which will come into force in January 2026, in addition to creating 50 measures to decarbonize the economy of the bloc's countries and strengthen the carbon market - Emissions Trading System (ETS) (EUROPEAN COMMISSION, 2019; HEREDIA; GALGANI, 2022).

Regarding the CBAM, the mechanism can affect important sectors of the Brazilian economy such as steel and iron (the focus of this research), in addition to the fertilizer, cement, aluminum, hydrogen, and electricity sectors (EUROPEAN COMMISSION, 2019; HEREDIA; GALGANI, 2022).

The CBAM is one of the strategies established by the European Union to tackle climate change, reducing GHG emissions and avoiding "carbon leakage", a practice that transfers GHG-intensive production from countries with stricter environmental laws to countries with more lenient environmental laws.

Thus, the implementation of the mechanism aims to equate products imported by the European Union with products manufactured in the country, with regard to compliance with environmental regulations and global decarbonization goals (EUROPEAN COMMISSION, 2021).

CBAM is part of the European Green Deal, created in 2019, which establishes goals for decarbonization, reducing GHG emissions by 55% by 2030 and neutralizing their effects by 2050 (CNI, 2024). This initiative also aims to prevent carbon leakage and equalize the rules followed by producers in the European Union (EU), taxing the ton of carbon incorporated into the exported product (CNI, 2024).

In addition, it is noted that important sectors will be affected by the implementation of the CBAM, such as the cement, fertilizer, hydrogen, electricity, aluminum, iron, and steel industries, as they will be required to track and provide information on the CO2 embedded in the products to be exported, making less carbon-intensive products more economically attractive (APEXBRASIL, 2023).

Faced with the consequences arising from GHG emissions, whether due to physical, financial, economic, and social risks, as well as creating an economic environment in the national scenario that promotes the strategy of inducing the transition to a low-carbon economy, Brazil, on December 11, 2024, sanctioned Law 15,042, which establishes the Brazilian Greenhouse Gas Emissions Trading System (SBCE), whose objective is to comply with the National Policy on Climate Change (PNMC) and the implementation of the agreements signed under the United Nations Framework Convention on Climate Change (BRASIL, 2024a).

The PNMC, created by Law N 12.187, of December 29, 2009, establishes guidelines that promote sustainable development and the reduction of greenhouse gas emissions. As part of this Policy, Brazil instituted, through Decree 11,550/2023, the Interministerial Committee on Climate Change (CIM), responsible for preparing the Climate Plan, which began in 2023, whose objective is to combat climate change, based on two pillars, the first being the mitigation of GHG emissions and the second, the adaptation of the population and structures to climate change (BRASIL, 2024b).

The Climate Plan will act strategically through Mitigation Plans and Adaptation Plans in a sectoral manner, in order to reach important sectors of the economy, generating an impact on the energy transition, sustainable industrial development, facing the climate crisis and migration to a low-carbon economy (BRASIL, 2024b).

In addition, the Climate Plan also has Cross-Cutting Strategies for climate change, aimed at reaching vulnerable populations, economic and environmental impacts, financing, monitoring and management, training, development and innovation. The Climate Plan has the collaboration of society, companies, government and academia, as well as more than 20 ministries, also supporting the preparation of the new Nationally Determined Contribution (NDC), with decarbonization goals in accordance with the Paris Agreement. (BRAZIL, 2024b).

In this sense, taking as a parameter the emissions recorded in 2005, Brazil has committed to reducing greenhouse gas emissions by 37% by 2025, and by 47% by 2030, ratifying the Paris Agreement - an agreement signed in 2015, whose objective is to combat climate change, keeping the global average temperature below 2ºC (ARTAXO, 2020).

For Unterstell and La Rovere (2021), the conformation of a change in this scenario requires policies focused on strategies to neutralize GHG emissions in the next three decades and, for this, two fronts need to be structured: (i) Change in industrial production processes and energy generation; and (ii) innovative public policies, committed to the transition to a less GHG-intensive economy.

In the steel sector, in view of the requirements on the carbon footprint incorporated in products exported to the European Union, the implementation of cleaner technologies is urgent (EUROPEAN COMMISSION, 2021), which can open opportunities for technological innovation and transfer of technologies developed in Scientific, Technological and Innovation Institutions (ICTs) to industries, through the Technological Innovation Centers (NITs) (FERREIRA; SOUZA, 2019), disseminating scientific and technological knowledge developed in academia, contributing to the technological adaptation of the productive sectors affected by the implementation of the Mechanism.

Paranhos, Cataldo and Andrade (2017) endorse that the performance of the NIT is fundamental for the approximation of universities to the productive sector, since this interaction is already part of government discussions when regulating its creation, aiming to support the development of science, technology and innovation. In this sense, the NIT becomes an important ally to the results of research developed within academia, by promoting dialogue with society, companies, and development institutions (QUEIROZ et al., 2022).

In addition, Queiroz et al. (2022) also highlight that, in order to be successful in achieving the attributions assigned to NITs in the management of intellectual property, in the production and transfer of technologies developed in ICTs, strategic planning and the promotion of a disruptive culture that stimulates interaction with the industrial sector are necessary.

Leite, Carvalho, and Oliveira (2023) state that NITs should play the role of catalyzing and disseminating innovations, in addition to integrating methods that process knowledge according to the technological needs of society, contributing to local, regional, and national development.

For Silva et al. (2015), technology transfer boils down to the promotion of technologies developed in sectors that do not have the same technological characteristics. In this context, the role of the NIT in intermediating the partnership between industry and ICTs can represent significant technological advances, allowing the anticipation of trends, the establishment of strategic partnerships, and the incorporation of sustainable innovations that can meet CBAM regulations

3 METHODOLOGY

3.1 CHARACTERIZATION OF THE RESEARCH

This article is characterized by a qualitative and exploratory approach, since it makes a bibliographic and documentary analysis on the subject. For contextualization and elaboration of the theoretical framework, institutional reports, legislation and scientific publications on cleaner technologies for the Brazilian steel industry were analyzed in relation to the Carbon Adjustment Mechanism at the Border of the European Union (CBAM/EU).

3.2 METHODOLOGICAL PROCEDURES

To achieve the objective of the research, three stages were followed, namely: stage 1 - bibliographic and documentary research; Stage 2 - Analysis and discussion of the results; and step 3 - final considerations.

Regarding stage 1, bibliographic reviews were carried out seeking to analyze, through dossiers and organizational reports, greenhouse gas emissions in the steel industry, government initiatives to address the climate crisis, and which studies have been developed for the development of cleaner technologies aimed at the decarbonization of the iron and steel industry.

To carry out the literature review, specialized search platforms such as SCOPUS, Capes Journals and Google Scholar were used, with keywords relevant to the topic, such as "climate change", "decarbonization in industry", "CBAM", "cleaner technologies", "the role of the NIT", in Portuguese and English, from January to July 2025.

In addition to articles referring to the proposed topic, manuals, reports, and government regulations that address the decarbonization process, greenhouse gas emission control policies, and the implementation of CBAM in Brazil were analyzed.

Still in stage 1, it was possible to build the theoretical and methodological framework of the research.

In relation to stage 2, data analysis and discussion were carried out. After a bibliographic and documentary survey, the information and data obtained were analyzed and discussed in order to be incorporated into the research.

In relation to stage 3, the final considerations were made and the limitations of the research were defined.

4 RESULTS AND DISCUSSIONS

Considering the global GHG neutrality goals, the carbon pricing imposed by the implementation of the CBAM, although challenging due to the short term for adaptation,

raises the development and application of cleaner technologies in the industrial sectors, since non-decarbonization will burden the price of products to be exported, generating a competitive, comparative, and relative disadvantage for Brazilian companies.

The transition to a low-carbon economy involves the migration from environmentally safe technologies, the so-called end-of-pipe, to the adoption of cleaner technologies, aiming at neutrality of emissions without negatively compromising production efficiency.

In this transition process, the need for technological innovation emerges, as well as technology transfer, which can be related to both tangible and intangible assets, especially in developing countries or industries that do not invest in R&D or face obstacles to adapting to the environmental regulations imposed, especially the CBAM.

Innovation, according to Law 10.973/2004, consists of the introduction of novelty or improvement of products in the production environment, which result in improvements and effective gains in quality or performance (BRASIL, 2004).

The results suggest that, even though Brazil is a country with a mostly renewable energy matrix, which should represent a competitive advantage over other countries with a predominance in a non-renewable energy matrix, the steel industry still depends on fossil fuels as an energy source for steel and iron production.

This scenario, given the pricing of the ton of carbon emitted per product, may pose challenges for competitiveness and compliance to adapt to the regulations imposed by CBAM. On the other hand, it opens up opportunities for innovation and development of cleaner technologies for decarbonization in industry, such as the use of green hydrogen as a renewable source of energy and the replacement of mineral coal with biomass to reduce iron ore in crude steel.

The Brazilian energy matrix and the new technological routes developed for decarbonization in the industrial sector enable competitive potential for adaptation and permanence in the export market, considering that Brazil is among the largest producers and exporters of steel products in the world (CNA, 2023).

In this sense, despite the predominance of conventional technologies, with the use of fossil fuels, the economic and environmental pressure generated by the implementation of CBAM with the pricing of the ton of carbon incorporated into products drives the development of cleaner technologies and the application of new technological routes for the transition to a low-carbon economy.

The electrification of processes, the use of green hydrogen to replace fossil fuels, and the better use of natural resources represent important strategies for the transition to a low-carbon economy in the steel industry. In the crude steel production process, the reduction of

iron ore in blast furnaces is the process identified as the most GHG emission intensive in the steel and iron sector (FERNANDES et al., 2024).

Therefore, the technology of using Electric Arc Furnace (EAF), with renewable energy, replacing conventional blast furnaces using coking coal, significantly reduces CO2 emissions (IEA, 2022). Another innovation is, in place of fossil fuels, the use of green hydrogen as a reducing agent in the Direct Reduced Iron (DRI) process, produced from renewable energy sources, can be a relevant strategy for the decarbonization of the industrial sector (IEA, 2025).

In addition, there are clean technologies, called end-of-pipe, which, according to Silva Júnior and Andrade (2011), seek to treat GHGs emitted after the production process, in order to reduce environmental impacts. Carbon capture and storage (CCS) and scrap metal recycling are examples of end-of-pipe technologies, as they act on the effect rather than the cause. Despite this, it is relevant strategies to mitigate the environmental impacts generated by GHG emissions in the steel industry, while cleaner technologies suggest changes in industrial processes in order to achieve both economic and environmental benefits (UNEP, 2016).

In this context, CCS, considered an end-of-pipe technology, consists of capturing, transporting and storing the carbon emitted in the production process in geologically safe locations, preventing GHGs from reaching the atmosphere (CÂMARA; ANDRADE; ROCHA, 2011), being a strategy for mitigating the environmental impacts resulting from CO2 emissions.

The carbon emitted can be compressed and transported by pipeline, ship, train or truck, if it is not used on site, being an alternative to sectors that have difficulties in reducing their emissions (IEA, 2022). Its application is used in the fertilizer industry, in addition to the production of synthetic carbon dioxide-based fuels, chemicals, and construction aggregates (IEA, 2022).

In the production of crude steel with a reduction in iron ore, CCS can be applied in the blast furnace route, since it is an emissions-intensive process. Another route of clean technologies or end-of-pipe consists of recycling scrap metal, considering that steel is a 100% recyclable material and can be reused several times, maintaining quality and being able to be transformed into various products (INSTITUTO AÇO BRASIL, 2023).

For the Brazilian Mining Institute (IBRAM, 2025), the development of technologies in the country is crucial for distancing itself from technological dependence. On the other hand, the analysis made by Cumming, Henriques and Sadorsky (2016) elucidates a possible obstacle that may justify the low adherence to clean technologies, although growing, but still

insufficient for sustainable development, when it portrays that companies already consolidated in the market and focused on fossil fuels would hardly be interested in investing in new technologies developed by start-up companies, Considering that investment in these technologies requires knowledge and experience to minimize economic risks.

According to Leite, Mendonça and Oliveira (2023), the NIT as a mediator between the productive and academic sectors is fundamental for the development of technologies that solve current problems in society, in addition to transferring technologies developed at the institution, registering patents and other intellectual property modalities.

Therefore, the NIT's role in the development of new technologies and technology transfer for the decarbonization of emission-intensive sectors can become fundamental for the transition to a low-carbon economy and the reduction of environmental impacts suffered by society, considering that, for Silva et al. (2015), scientific and governmental institutions must develop technology transfer strategies associated with the demands of industries.

In this sense, NITs can act as a central actor in the articulation and integration between ICTs and the steel sector, performing a function that goes beyond the mere management of innovation and protection of the intellectual property of these institutions, that is, a strategic and proactive role. In the face of CBAM's regulatory pressures, NIT needs to act as a protagonist in mapping technological gaps in the industry, at the local, regional and national levels, connecting them to inventions, scientific and technological research, as well as to the skills available in ICTs.

From this perspective, it is envisaged that the NITs can build innovation roadmaps in clean technologies, functioning as an actor-guide of the productive sector on which technologies can support decarbonization, what is the technological readiness level (NPT) or the English Technology Readiness Level (TRL) of these technologies, channeling initiatives and also pointing out which ones require co-development and how they can be transferred (NASCIMENTO, 2021; HORA, 2021; SANTOS, 2024).

One dimension to be considered in the performance of NITs in the context of CBAM is the strategic role as an actor in specialized technological curatorship, both from the perspective of prospecting and from the perspective of compliance with the technical dimensions of the inventions, as well as their adherence to the rules and restrictive carbon assumptions imposed by CBAM.

Thus, the role of the NIT also gains contour as an actor in the conversion and translation of scientific and technological results into regulatory and economic language, evaluating the potential for reducing emissions, energy efficiency gains or substitution of inputs and their alignment with global requirements in the context of the low-carbon economy

in Brazil and in the world. By performing this role of institutional translator in ICTs, NITs reduce information asymmetries between academia and steel mills, creating conditions for clean technologies to leave laboratories and enter industrial processes.

The research by Guimarães (2013), Ferreira (2019), Nascimento (2021) and Hora (2021), as well as Santos (2024), pointed out that the NITs encounter difficulties ranging from the professionalization of management, with high staff turnover, as well as difficulties in operationalizing negotiation, valuation and marketing strategies that are important in technology transfer. In this sense, the fundamental role of NITs as a technological risk mediator stands out, fundamental in the steel sector, where investment decisions are capital-intensive.

To this end, it is necessary to professionalize the NITs that enable them to use strategic and advanced tools of finance and negotiation, through technological valuation methods, such as methodologies such as real options, discounted cash flows, multicriteria environmental impact analyses and TRL models integrated with the regulatory risk of CBAM, offering objective instruments for steel mills to decide which technologies they should license, acquire, test or code in pilot projects.

This mediation reduces the risk of adopting immature technologies and increases the predictability of environmental and economic returns, an essential element in the new carbon tariff scenario, in addition to channeling resources more efficiently in the development and production of new technologies in Brazil.

Another dimension of strategic action of NITs is the governance of partnerships and technology transfer contracts, through disruptive models that can break the bureaucratic barriers that currently exist in public ICTs. With the development of models appropriate to the environmental context, elements such as the construction of environmental performance clauses, risk sharing mechanisms, such as licenses conditioned to carbon metrics, among others, need to be incorporated in the face of the regulatory context.

In addition, this can give NITs not only the role of acting in technology transfer, but also in the construction of safe institutional environments so that Brazilian industry can adapt to the energy transition route required by the CBAM context.

Finally, it is necessary that ICTs, through NITs, act in a more inductive way in the Brazilian innovation ecosystem, through the articulation of actors such as industries, such as steel mills, research centers and institutes, government, environmental agencies, regulatory agencies and investors, promoting initiatives such as technological calls, open innovation environment, among other initiatives, with the objective of enabling the construction of a route of solutions aligned with CBAM.

In summary, Table 1 presents the possible roles of NITs in the context of the Brazilian steel industries in relation to the CBAM.

Table 1

Role, Actions and Strategies of the NIT for Cleaner Technologies in the Steel Industry in relation to CBAM

Role of the NIT	Key Actions	Associated Strategies
Diagnosis and Technological Mapping	Identify technological gaps in the steel sector; map TRLs of clean technologies available in ICTs; analyze bottlenecks in emissions, energy and inputs in the sector.	Develop decarbonization technology roadmaps; create a technology bank aligned with CBAM; structure a strategic portfolio of inventions with potential for industrial application.
Technical-Regulatory Curation	Evaluate adherence of technologies to carbon metrics and CBAM criteria; translating scientific results into regulatory and economic language; prepare environmental and technological impact opinions.	Develop CBAM-technologies compliance matrix; create a validated catalogue of green solutions; institute technical opinions on eligibility for technology transfer aimed at decarbonization.
Mediation of Technological and Economic Risks	Apply technological valuation; perform technical and environmental analysis (due diligence); to build scenarios of economic impact of CBAM for the industry.	Create integrated TRL + Valuation + Carbon Risk models; produce due diligence reports for steel mills; support decisions on licensing, co-development and industrial pilots.
Legal and Contractual Governance of Technology Transfer	Structure TT contracts with environmental performance clauses; define royalties linked to the reduction of emissions; create licenses conditioned to carbon metrics; negotiate co-development agreements.	Implement green intellectual property contracts; adopt contractual models with regulatory risk sharing; structure mechanisms to protect and encourage environmental performance.
Orchestration of Green Innovation Ecosystems	Articulate ICTs, steel mills, startups, R&D centers and government; promote public calls, technological challenges and pilot projects; encourage consortia and collaborative platforms.	Create a sectoral innovation platform focused on cleaner technology; coordinate open innovation environments and R&D routes; foster climate spin-offs and experimental environments to accelerate technological maturation.

Source: Prepared by the authors based on research data (2025).

Such strategies can promote sustainable development, assisting in the technological and regulatory adaptation of the sectors affected by CBAM, enabling the competitiveness of Brazilian companies in the export market to the European Union.

5 CONCLUSION

This research aimed to analyze the role of the Technological Innovation Center (NIT), linked to the Scientific, Technological and Innovation Institutions (ICTs) as an inducer of the development of cleaner technologies in the steel sector. To this end, an exploratory research

was carried out, with a bibliographic and documentary approach, as well as a qualitative nature.

The research pointed to the fact that the implementation of the European Union Border Carbon Adjustment Mechanism may pose challenges to GHG-intensive sectors if they are unable to adapt technologically to the monitoring and reduction of embodied carbon in products exported to the European Union. In this sense, CBAM can also open opportunities for technological innovation and transfer of cleaner technologies that can be applied in industry for the decarbonization of sectors, otherwise they will lose competitiveness in the European market.

For the present research, bibliographic and documentary reviews were carried out on the impacts of CBAM, the technological routes used in the production of steel and iron, the implementation of cleaner technologies and decarbonization in the industry. The steel sector still depends on fossil fuels, even though Brazil has a mostly renewable energy matrix. The literature presents cleaner technologies as alternative routes for decarbonization in the reduction of iron ore for crude steel production, with the use of green hydrogen as an energy source and the replacement of fossil fuel with biomass.

The transition to a low-carbon economy involves the transfer of conventional or clean technologies to cleaner technologies, which, for Silva Júnior and Andrade (2011), requires greater investment in research, development and innovation. In this sense, NITs can play a fundamental role in the development and implementation of cleaner technologies to adapt to CBAM regulations and achieve global decarbonization goals, mediating scientific production and the productive sector.

The present research is limited to analyzing the cleanest technologies applicable to the steel sector for decarbonization in relation to CBAM. Further research may be directed to exploring which technology transfers are being carried out in the steel industry and what are their economic and technological impacts for adaptation, in addition to analyzing the effective participation of NITs in this process.

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