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BOOK OF PROCEEDINGS

—

IX Congresso Ibero-Americano de Empreendedorismo, Energia, Ambiente e Tecnologia (CIEEMAT 2025).

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Scientific and technological analysis of the biogas sector from a global perspective: research and innovation trends

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ABSTRACT

The growing global interest in renewable energy sources has driven research and development of technologies aimed at reducing greenhouse gas emissions and decreasing dependence on fossil fuels. In this context, biogas emerges as a promising alternative, offering a viable solution for managing organic waste and generating energy. This research aimed to provide a comprehensive global overview of the biogas sector through the analysis of scientific and technological information available in databases of articles and patents. The data were analyzed under two dimensions: scientific and technological maturity; research, development and innovation pathways. The results showed that the biogas sector has experienced significant growth in recent decades, primarily driven by national and regional public incentives since 2005. Despite a certain cooling of patenting activities in recent years, there has been a strong increase in investments, especially in Europe, due to the war between Russia and Ukraine, causing several countries to redirect resources to reduce international dependence on natural gas. Among the main factors causing this phenomenon are the geopolitical dispute over oil and international pressure for new models of energy generation. China stands out as the main source of this technological and scientific development, but the USA, Germany, and Japan also have a strong presence in this ecosystem. This research also showed that renewable energy and the biogas sector, specifically, are sensitive to public incentives and regulatory policies, with their implementation having a direct influence on the production of scientific novelties and technological innovations.

KEYWORDS

Biogas; Renewable Energy; Innovation

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Improving Public Procurement Sustainability with a Plug-in

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ABSTRACT

This study addresses the challenge of integrating environmental sustainability into public procurement by proposing and evaluating a digital plug-in tool designed for Brazil's federal procurement system, Compras.gov.br. Aligned with the Design Science Research (DSR) methodology, the research involved multiple phases, including the identification of sustainability criteria through a systematic literature review based on the PRISMA protocol. A total of 31 criteria were identified and categorized into environmental, social, and governance (ESG) dimensions, with the environmental aspect prioritized for this prototype development. The environmental criteria were further organized according to a life cycle approach and translated into specific requirements based on national and international references, such as the Brazilian National Guide for Sustainable Procurement and the Blue Angel eco-label. These requirements were then mapped to a list of 14,750 categorized items, corresponding to approximately 10% of the federal procurement catalog, enabling the tool to provide context-specific recommendations. Initial testing involved 12 users across seven campuses of a federal educational institution, with feedback collection underway. Although limited to one institution and focused solely on environmental criteria, the plug-in demonstrates the potential of digital innovations to operationalize sustainability in public procurement. Future iterations may expand its scope and applicability to incorporate social and governance dimensions.

KEYWORDS

Sustainable Public Procurement, Design Science Research (DSR), Digital Plug-in tool.

INTRODUCTION

Public procurement plays a pivotal role in achieving sustainable development goals (SDGs), given the significant volume of government purchases and their impact not only on economic but also on social and environmental systems[1]. As highlighted by the United Nations and the OECD, integrating sustainability into public procurement processes is essential to promote responsible production and consumption, reduce environmental degradation, and encourage innovation. In Brazil, legislative frameworks such as the new Procurement Law (Law No. 14.133/2021), the "Política Nacional de Resíduos Sólidos (PNRS)", and the "Política Nacional de Mudanças Climáticas (PNMC)" emphasize the need to incorporate sustainability criteria into procurement decisions. However, as highlighted by [1], despite this normative progress, it remains limited and the sustainable procurement practices still considered as a non-mandatory field.

These initiatives aim to enhance the ESG (Environmental, Social, and Governance) performance of public institutions. ESG serves as a framework for assessing sustainable and green development within organizations, encouraging them to take on environmental, social, and governance responsibilities while generating positive and sustainable impacts [2], [3].

Sustainable Public Procurement (SPP) is defined as the process by which public authorities seek to procure goods, services, and works with a reduced environmental impact throughout their life cycle, while also promoting social and economic benefits [4]. Environmental criteria typically include energy efficiency, recyclability, use of renewable materials, and the reduction of hazardous substances. Nevertheless, multiple studies have identified barriers to effective SPP implementation, including limited technical knowledge, lack of standardized criteria, institutional inertia, and the perception that sustainable products are more expensive [5]. Additionally, as observed by [6] procurement agents often face challenges in translating high-level sustainability goals into actionable requirements in tender documents, especially during the planning and specification stages.

The complexity of integrating life cycle and environmental considerations into procurement decisions demands adequate support mechanisms. In this context, the use of technological innovation tools can play a vital role in bridging the gap between policy and practice [7]. Several international initiatives have developed databases and toolkits to guide sustainable choices (e.g., the Green Public Procurement Toolkit, Ecoinvent, and EU GPP Criteria). However, these resources often require specialized knowledge and may not be adapted to local regulatory frameworks or procurement systems.

Technological innovation in procurement—through the adoption of e-procurement platforms, data analytics, and AI—has shown potential to increase transparency, efficiency, and compliance with sustainability mandates [7]. Digital tools can automate repetitive tasks, suggest sustainable alternatives, and provide real-time feedback to users. Despite these advancements, there remains a lack of user-friendly, embedded tools designed specifically to assist procurement officers in identifying and applying sustainability criteria at the point of decision-making, particularly in the Brazilian context.

Within the framework of Law No. 14,133/2021 — the new Brazilian Public Procurement Law — a significant advancement in the modernization of public administration is represented by the establishment of the National Public Procurement Portal (PNCP). As mandated by the new legislation, the PNCP is intended to function as a digital platform for the mandatory disclosure of procurement procedures and electronic contracting processes, applicable across the Executive, Legislative, and Judiciary branches (PNCP, 2023).

Although the Brazilian public sector has access to a digital system that is generally favorable to the implementation of technological solutions, [8] point out that a significant limitation lies in the limited technical ex\pertise of public professionals. This lack of technical capacity hinders the effective adoption of technology by government entities. Furthermore, existing legal frameworks often pose additional challenges, creating barriers to the incorporation of innovations and technological advancements into public administration.

To address the challenges of incorporating environmental criteria into public procurement processes, this study proposes a plug-in tool designed to support decision-making within the Brazilian federal procurement platform, Compras.gov.br. The plug-in functions as a browser extension that integrates with the existing system interface, identifying the product or service being purchased through its CATMAT or CATSER classification code and automatically displaying relevant sustainability criteria based on life cycle considerations. By providing tailored environmental recommendations, the proposed tool can guide procurement officers on the requirements that should be included in the preparatory documents of the procurement processes. This innovative solution contributes to bridging the gap between policy and practice, enhancing the operationalization of sustainable procurement and promoting environmentally responsible decision-making within the public sector.

The following section outlines the research method adopted in this study, detailing the procedures and strategies used to achieve the research objectives. It then presents the main findings and offers a critical discussion of the results in light of the existing literature and the study's theoretical framework. Finally, the section concludes by summarizing the key contributions, acknowledging limitations, and suggesting directions for future research.

Research Method

The present research adopts an interventionist and constructive approach, as it was designed to propose, develop, and evaluate practical solutions grounded in scientific knowledge. To this end, and following the framework proposed by [9], the study employed a multi-phase methodological process to develop a digital tool that supports the integration of environmental sustainability criteria into public procurement processes. This approach aligns with the Design Science Research (DSR) methodology, which is widely used in information systems, engineering, and related fields for the development and evaluation of innovative artifacts aimed at addressing real-world problems.

Figure 1 presents the research stages, which were structured based on the Design Science Research (DSR) methodology, as proposed by [9]: Problem Identification and Motivation, Objectives of a Solution, Design and Development, Demonstration, Evaluation, and Communication.

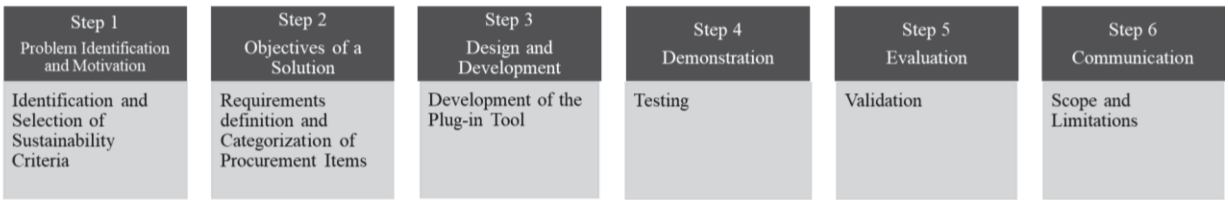


Fig. 1. Research stages

The process began with the identification of the problem and its underlying motivation, grounded in the need to incorporate sustainability criteria into public procurement processes. Subsequently, the objectives of the solution were defined through the identification and selection of relevant sustainability criteria, as well as the categorization of procurement items. The development phase resulted in the construction of the artifact: a plug-in designed to support decision-makers during the acquisition process. The demonstration of the tool and its preliminary evaluation are being carried out through user testing, allowing for an assessment of its applicability and effectiveness. Finally, the results, its limitations, and the contributions from this work will be analyzed and communicated, in alignment with the final stages of the DSR cycle.

By employing DSR, this study bridges the gap between sustainability theory and the practical needs of procurement agents, delivering a digital tool that facilitates the operationalization of environmental criteria within Brazil's public procurement system.

Results

In Step 1, for the identification and selection of sustainability criteria, a systematic literature review was carried out using the PRISMA protocol (Preferred Reporting Items for Systematic Reviews and Meta-Analyses). The PRISMA protocol is recognized for performing systematic literature reviews [10] and this approach was employed to explore topics and content related to this subject. The PRISMA method consists of four phases: Identification, Screening, Eligibility, and Inclusion, as illustrated in Figure 2.

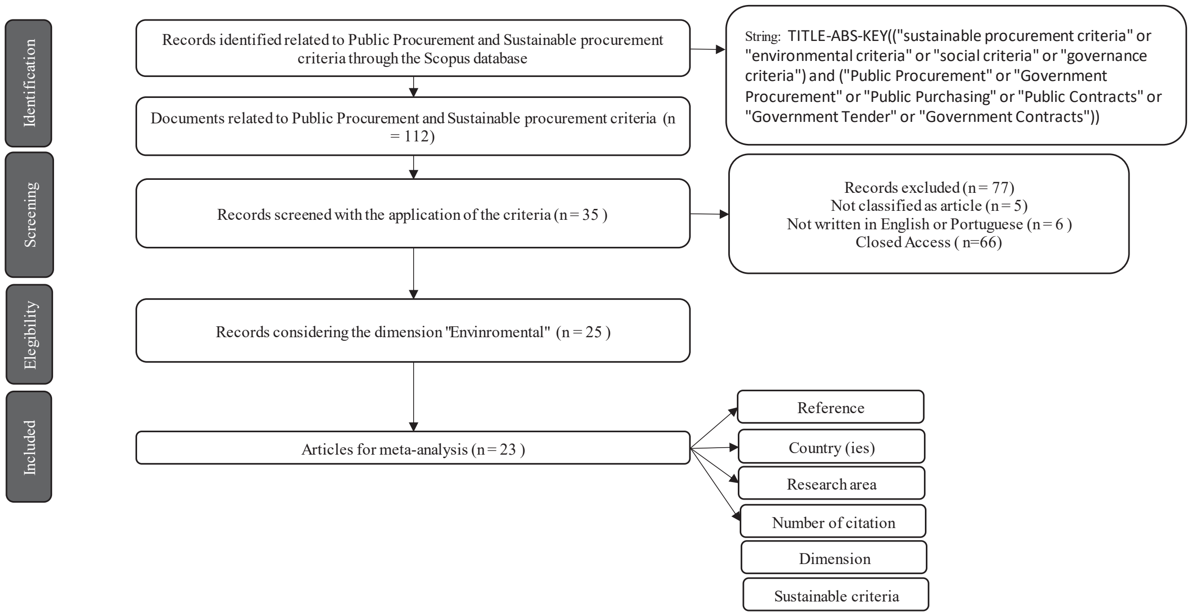


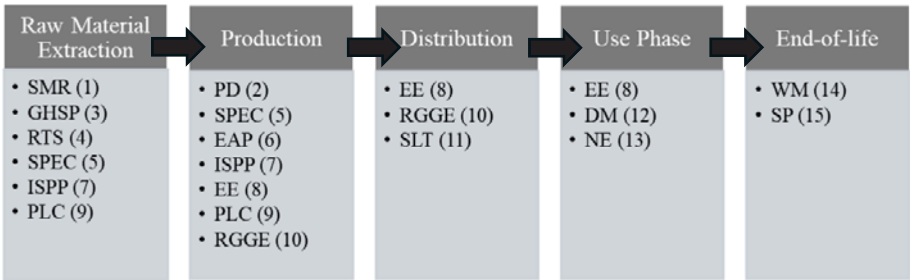
Fig. 2. PRISMA method considering Sustainable Procurement criteria and Public Procurement

During the Identification phase, search terms were strategically defined based on expert input and the research unit's knowledge and applied in the Scopus database using a comprehensive search string targeting the sustainability criterion in public procurement. Scopus was selected due to its extensive multidisciplinary coverage, suitable for the cross-sectoral nature of the topic. Despite the suitability of other databases, preliminary analysis indicated significant overlap, justifying the exclusive use of Scopus. In the Screening phase, 112 open-access articles in English or Portuguese were initially retrieved, and 35 were retained after applying predefined refinement criteria. The Eligibility phase involved a detailed review of titles and abstracts to identify the presence of environmental criteria, leading to the exclusion of 12 documents and the selection of 23 articles for further analysis. Finally, in the Inclusion phase, the selected articles underwent full-text reading and in-depth evaluation by the authors for subsequent meta-analysis.

From this literature review, 31 criteria were defined, organized into three main dimensions—environmental, social, and governance—directly reflecting the pillars of the ESG approach. The environmental dimension includes: Sustainable Material Resources (SMR); Green and healthy standards for products (GHSP); Reduction of toxic substances (RTS); Sustainable production and environmental certifications (SPEC); Implementation of sustainable public policies (ISPP); Product life cycle (PLC); Product Design (PD); Environmental Action Plan (EAP); Energy Efficiency (EE); Reduction of greenhouse gas emissions (RGGE); Sustainable logistic and transportation (SLT); Durability and Maintainability (DM); Noise Emissions (NE); Waste Management (WM); Sustainable Packing (SP). The social dimension highlighted the role of public procurement as a tool for equity and social justice, including: Working Conditions (WC), Equal opportunities (EO); Social Responsibility (SR); Inclusion of minorities and marginalized populations (IMMP) and Promotion of local development (PLD). Finally, the governance dimension includes elements such as: Compliance with legislation (CL); Integrity and anti-corruption (IAC) and Risk Management (RM).

It is important to emphasize that, for the development of the plug-in, the study initially focused on analyzing environmental requirements within procurement processes. This focus was due to the extensive workload involved in identifying, organizing, and integrating sustainability criteria into a digital tool. Prioritizing environmental aspects allowed for a more manageable and methodologically sound starting point, without excluding the possibility of incorporating social and governance dimensions in future stages.

In this sense, the environmental criteria were identified based on the life cycle approach, considering the various stages, from "cradle to grave". Figure 3 presents the distribution of these criteria across the respective life cycle phases, following a general and didactic structure. It is worth noting, however, that certain criteria may apply to more than one phase, depending on the specific context of the product or service being evaluated. As for social and governance criteria, they are understood as cross-cutting dimensions that are essential throughout the entire life cycle.



Note: SMR: Sustainable Material Resources; GHSP: Green and healthy standards for products; RTS: Reduction of toxic substances; SPEC: Sustainable production and environmental certifications; ISPP: Implementation of sustainable public policies; PLC: Product life cycle; PD: Product Design; EAP: Environmental Action Plan; EE: Energy Efficiency; RGGE: Reduction of greenhouse gas emissions; SLT: Sustainable logistic and transportation; DM: Durability and Maintainability; NE: Noise Emissions; WM: Waste Management; SP: Sustainable Packing.

Fig. 3. Environmental criteria in Product life cycle

In the requirements definition and categorization phase, based on the 31 identified criteria, requirements were established through content analysis from two sources: the National Guide for Sustainable Procurement and the Blue Angel (Blauer Engel) website. As emphasized by [11], it is essential to consider each country's specific context when defining evaluation criteria, ensuring that they address the unique realities of individual organizations. The National Guide for Sustainable Procurement was selected as a key reference for Brazil. Developed by the Office of the Comptroller General (CGU), this guide serves as a practical compilation of guidelines adapted to the Brazilian context, offering public managers insights and directions for implementing sustainable public procurement practices [12]. Blue Angel, a globally recognized standard for defining sustainability criteria, was the second source consulted for content analysis. These criteria are established by an independent jury, comprising industry experts, environmental protection organizations, and consumer associations [13]. Table 1 presents the requirements considered for each sustainability criterion.

Table. 2. Sustainable Procurement Criteria and Requirements

Domain	Criteria	Requirement
Environmental	Sustainable use of material resources	This refers to the use of recyclable materials or the requirement for a certificate of material origin (e.g., FSC).
	Product Design	Reference to product design development considering of reuse, recycling, refilling or reusability.
	Green and health standards for products	Reference to the low emission of volatile organic compounds (VOCs) or similar.
	Reduction of toxic substances	Reference to the non-use of toxic substances such as lead, mercury, among others
	Sustainable production and environmental certifications	Reference to the registration in the Federal Technical Registry of Potentially Polluting Activities or other certifications (e.g., ISO 14.001).
	Environmental action plan	Presentation of an environmental action plan to reduce or mitigate environmental issues and ensure compliance with requirement
	Implementation of sustainable public policies	Reference to the public policies such as National Energy Conservation Label (ENCE) with an efficiency class of A, as per INMETRO regulations or others.

	Energy Efficiency	Reference to or concern with energy efficiency in the production process.
	Product life cycle	Requirement for the presentation of a product life cycle analysis.
	Reduction of greenhouse gas emissions	Reference to or concern with the adoption of manufacturing processes that reduce pollutant emissions.
	Sustainable logistics and transportation	Reference to or concern with reverse logistics and other sustainable practices in the supply chain.
	Durability and maintainability	Reference to the need for compliance with INMETRO standards on durability.
	Noise Emission	Reference to the need for CONAMA Resolutions and related legislation on noise standards
	Waste management	Reference to or concern with the National Solid Waste Management Information System (SINIR) rules
	Sustainable packing	Reference to or concern with the use of internal protective materials in packaging that are recyclable, biodegradable, and eco-friendly.
Social	Working condition/	Report containing information on working conditions, such as workplace accident rates, training, and others.
	Equal opportunities	Reference to or concern with actions that promote gender equity in the workplace.
	Social Responsibility/	Reference to or concern with actions that promote local social.
	Inclusion of minorities and marginalized populations	Reference to or concern with actions that promote the inclusion of minorities or marginalized populations, such as compliance with the minimum percentage of the workforce composed of women who are victims of domestic violence.
	Promotion of local development	In reference to or concern with projects that promote local development, such as participation in the Computers for Inclusion Program,
Governance	Compliance with legislation	Presentation of the declaration report with the bidders' obligations regarding compliance with legal regulations.
	Integrity and anti-corruption	Reference to or concern with the compliance of bidders with anti-corruption practices.
	Risk Management	Presentation of procurement risk management.

The authors of [8] conducted a categorization to facilitate content analysis. Similarly, procurement processes were categorized to support the definition of environmental criteria. As shown in Table 2, the following categories of products and services were considered for constructing the baseline list used in plug-in development. These categories were based on existing classifications, such as Brazil's CATMAT (Material Classification Table) and CATSER (Service Classification Table), enabling precise mapping between item types and applicable environmental criteria. This step was essential to ensure that the tool's recommendations would be relevant and context-specific. According to the table, 14,750 items were included in the baseline list, representing approximately 10% of the total items in the federal procurement catalog.

Table. 2. Category and Sub-category considered

Category	Sub-category	Qty
Material	Components of Electrical and Electronic Equipment	223
	Electrical Conductors and Equipment for Power Generation and Distribution	75
	Lighting Equipment and Lamps	536
	Workshop Equipment for Maintenance and Repairs	68
	Equipment for Preparing and Serving Food	142
	Equipment for Refrigeration, Air Conditioning, and Air Circulation	717
	Information Technology – Equipment, Parts, Accessories, and ICT Supplies	3293
	Musical Instruments, Phonographs, and Domestic Radios	60
	Manufactured Non-Metallic Materials	160
	Furniture	1868
	Tires and Inner Tubes	226
	Substances and Chemical Products	7248

	Office Utensils and Supplies	74
	Vehicles	16
Service	Personnel Service Provision	1
	Specialized Cleaning Services	5
	Management Services in Information and Communication Technology (ICT)	6
	Consulting Services in Information and Communication Technology (ICT)	5
	Support Services in Information and Communication Technology (ICT)	1
	Data and ICT Indicators Analysis Services	3
	Tour Guide Services	2
	Hosting Services in Information and Communication Technology (ICT)	6
	Systems Integration Services in Information and Communication Technology (ICT)	1
	Maintenance and Installation Services for ICT Equipment	6
	Research, Analysis, and Development Services in Information and Communication Technology (ICT)	2
	Project Services in Information and Communication Technology (ICT)	3
	General Cleaning Services	1
	Services for Information and Communication Technology (ICT) Infrastructure, Not Classified Elsewhere	2
	TOTAL	**14750**

In Step 3, related to the development of the Plug-in tool, a Chrome browser extension was created as a proof of concept to enhance user interaction with the Brazilian government's public purchasing catalog website. Specifically targeting the URL https://catalogo.compras.gov.br/cnbs-web/busca, the extension uses a content script (scripts/content.js) to inject JavaScript directly into the webpage. This script interacts with the page's content via the Document Object Model (DOM), allowing the plugin to dynamically read, interpret, and modify information displayed to the user. Leveraging such features, it annotates catalog items based on preloaded criteria. The plugin structure adheres to standard Chrome extension architecture defined by Manifest V3. The `manifest.json` defines the metadata, permissions, and script injection rules. The `resources` folder contains a local JSON database (`acv_db.json`), enabling the plugin to match and annotate catalog data locally. Overall, the plugin is lightweight and modular, designed for a specific use case with potential for expansion. The codebase is structured for clarity and modularity, with an emphasis on maintainability and potential for future enhancements. Designed with institutional use in mind, the plugin demonstrates an efficient, targeted application of browser extension technologies in the public sector, following current best practices for secure and focused web augmentation.

The next step, in the Testing and Validation phase, the initial testing was conducted through the presentation of the plug-in and an explanation of the tool's purpose, which is to enable the practical application of environmental criteria within procurement processes. The proposal was presented to 12 users, with the plug-in successfully installed on 12 computers. These sessions were held both in person and remotely via the Microsoft Teams platform. User selection was based on familiarity with public procurement within a public educational institution, covering 7 of the 8 campuses where the institution operates.

The plug-in is currently in the validation phase, during which user feedback will be collected to inform adjustments aimed at improving both user experience and tool functionality. This testing period is expected to last approximately two months.

The final phase of the research addresses the scope and limitations of the study. This work focused exclusively on environmental criteria, intentionally deferring the integration of social and governance dimensions to future development stages. The plug-in functions as a foundational prototype, demonstrating the potential of digital tools to embed sustainability into public procurement processes. Scalability and broader applicability are anticipated in future iterations. It is important to note, however, that the validation and testing were carried out within a single government institution, which represents a limitation in terms of the generalizability of the findings.

Interpretation of Findings

The results of this study demonstrate the feasibility and relevance of integrating sustainability into public procurement processes through digital innovation. The development of the plug-in, guided by the Design Science Research (DSR) methodology, illustrates how theoretical concepts such as ESG and life cycle thinking can be translated into practical decision-support tools. By narrowing the focus to environmental criteria, the research team was able to develop a functional and targeted artifact, making procurement planning more manageable. The systematic selection of criteria and their alignment with item categories ensure that the tool provides concrete and applicable guidance for procurement professionals.

As illustrated in Figure 4, once the plug-in is installed and the user accesses the Brazilian federal government's procurement catalog website, the procurement officer can verify the relevant sustainability criteria associated with the material or service being acquired, which should be incorporated into the item specification within the Terms of Reference. In this prototype version, only environmental criteria are displayed. It is important to emphasize that social and governance criteria should be incorporated in future research efforts to enable a more comprehensive application of the ESG approach, rather than focusing solely on environmental aspects.

Fig. 4. Screen of the plug-in from the Brazilian federal government procurement catalog website.

User engagement during the initial testing phase confirmed a positive reception regarding the perceived value of the tool. However, the results also highlight the challenges associated with implementing such innovations in the public sector, including variability in digital literacy and the rigidity of existing procurement platforms. Moreover, despite strong legislative support for sustainability in Brazilian public procurement, the operational translation of these principles remains limited in the absence of adequate training and integrated support tools.

This discussion reinforces the importance of co-developing technological solutions with the procurement stakeholders themselves to ensure alignment with real-world constraints and practices. Although this initial version of the tool addresses only environmental considerations, its structure is adaptable and scalable. Future efforts should focus on incorporating social and governance dimensions, as well as expanding testing across different institutional contexts to enhance generalizability and effectiveness.

Another important point to consider is that, as a prototype, the proposed solution requires articulation with the technical teams responsible for public procurement to ensure its proper understanding, acceptance, and use. Furthermore, the implementation and maintenance of the tool must be attributed to a central authority with the technical and institutional capacity to ensure the continuous updating of criteria and full integration with official procurement systems. In this regard, public policies aimed at the digital transformation of public administration, such as the Federal Government's Digital Government Strategy, can provide the necessary support for institutionalizing the tool. Such alignment contributes not only to the consolidation of innovation but also to its scalability and long-term sustainability.

Conclusion

This study contributes to the field of sustainable public procurement by presenting a digital plug-in tool that bridges the gap between policy and practice. By adopting a structured research methodology focusing on environmental sustainability, the project delivers an innovative and practical solution tailored to the Brazilian federal procurement context. The categorization of items, mapping of criteria, and integration with the existing Compras.gov.br system represent significant advances toward embedding sustainability at the core of procurement decisions.

The plug-in prototype demonstrates how digital tools can empower procurement agents, offering context-sensitive criteria that support more environmentally responsible choices. Although the current version is limited in scope and validation, the results are promising and provide a solid foundation for future refinement and expansion. The emphasis on user-centered design and practical applicability enhances the tool's relevance and usability.

In conclusion, the study underscores the transformative potential of technological innovation in public procurement. By enabling the operationalization of sustainability principles, the plug-in supports institutional efforts to comply with legal frameworks and broader sustainability goals. Future research should explore integration with broader ESG frameworks, expand testing in diverse institutional settings, and assess long-term impacts on procurement practices and environmental outcomes.

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Energy Efficiency Assessment of a Youth Hostel Based on Multizone Modeling and Simulation

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ABSTRACT

This paper presents an energy performance assessment of a youth hostel in northern Portugal through multizone dynamic simulation. The study combines on-site data collection, energy billing analysis, and advanced building modeling in DesignBuilder using EnergyPlus as the calculation engine. The model includes the building envelope, occupancy profiles, internal loads, HVAC systems, lighting schedules, and domestic hot water production. The simulation results reveal that heating demand is strongly concentrated on the ground floor, with a total installed capacity of 51.04 kW after applying the required safety factor. Lighting contributes minimally to internal gains due to the exclusive use of efficient LED fixtures with occupancy sensors. Annual CO_2 emissions were estimated at 84.21 tonnes, highlighting the building's environmental impact. The results demonstrate the relevance of dynamic simulation as a decision-support tool for optimizing energy performance, reducing operational costs, and prioritizing future retrofit measures in similar hospitality buildings.

KEYWORDS

Dynamic Building Simulation, Energy Efficiency Assessment, Youth Hostel Retrofit.

INTRODUCTION

The building sector accounts for a significant share of global final energy consumption and greenhouse gas (GHG) emissions, making energy efficiency a central pillar of European and national climate policies. The EU's Energy Performance of Buildings Directive (EPBD) establishes a framework for assessing and improving building energy performance, promoting the reduction of energy demand and the decarbonization of the sector. In this context, dynamic simulation tools have become essential for predicting energy use under realistic operating conditions and for supporting the design and management of efficient buildings.

Multizone dynamic simulation enables the accurate representation of thermal zones, internal loads, and HVAC operation schedules, providing detailed insights into heating and cooling needs, internal gains, and overall energy consumption. This approach allows building professionals to test different design alternatives, optimize system operation, and evaluate the potential of retrofit strategies before implementation.

This paper focuses on the energy performance assessment of a youth hostel in northern Portugal, combining field data collection, energy billing analysis, and detailed modeling using DesignBuilder with EnergyPlus as the calculation engine. The primary objective is to calibrate and validate a simulation model that accurately represents the building's energy behavior, quantify energy needs and associated CO_2 emissions, and identify key areas for improvement. The results provide a foundation for proposing energy efficiency measures that can reduce operating costs and support the transition toward a more sustainable hospitality sector.

WORK CONTEXTUALIZATION

The initial steps toward improving the energy performance of tourism and hospitality buildings in Europe were undertaken during the late 1970s and early 1980s in several countries (e.g., France, Denmark, the then Federal Republic of Germany, and the Netherlands). However, it was only with the adoption of the Energy Performance of Buildings Directive (EPBD) in 2002 that a unified EU-wide policy emerged [1]. This directive was later complemented by the Energy Services Directive in 2006 [2], which was replaced by the Energy Efficiency Directive (EED) in 2012.

The EU's comprehensive and integrated energy policy framework was further strengthened with the introduction of the ”Clean Energy for All Europeans” package [3]. This legislative package consolidates policies related to energy efficiency, renewable energy, electricity markets, and international cooperation. It includes amendments to the EED [4], the EPBD [5], and the Renewable Energy Directive (RED) [6]. These initiatives aim to reduce the environmental impact of energy consumption while maintaining or improving indoor comfort and air quality and addressing energy poverty issues.

In the tourism sector, the use of renewable energy technologies such as solar panels, biomass heating, and efficient HVAC systems can significantly reduce operating costs and carbon emissions. EU regulations, particularly the RED III and EPBD, emphasize integrating renewables in both new and existing buildings to achieve nearly zero-energy standards.

Although Portugal was relatively late in adopting energy efficiency measures in tourism and hospitality sectors, it has made significant progress in both regulatory frameworks and efficiency programs. Notably, three main energy efficiency initiatives have been implemented: the Home Renewable Programme, the Energy Certification of Buildings, and the Renewable at the Time Programme [7] and [8]. The EPBD was first transposed into Portuguese law in 2006 through three separate decree-laws, covering certification systems, performance in commercial and service buildings, and performance in residential buildings [9], [10] and [11]. In 2013, a single legislative document, Decree-Law No. 118/2013, was introduced to align the national regulations with the requirements of the 2010 EPBD amendment [12]. As a signatory of the Paris Climate Agreement, Portugal has committed to contributing to the European Union's efforts to mitigate greenhouse gas (GHG) emissions, aiming to limit global temperature rise to well below 2◦C compared to pre-industrial levels [13]. Globally, the energy sector is a major contributor to GHG emissions, accounting for approximately two-thirds of emissions in 2014 [14]. In the European Union (EU), buildings represent a significant share of the environmental burden, responsible for around 36% of CO_2 emissions and nearly 40% of total energy consumption. Among these, the residential and hospitality sectors alone accounted for a substantial portion of the EU's final energy consumption in 2014 [4].

Portugal transposed European Directive (EU) 2018/844 and partially Directive (EU) 2019/944 into national legislation on 7 December 2020 in order to establish the requirements applicable to buildings to improve their energy performance and regulate the Energy Certification System for Buildings in Portugal [15], having been subsequently amended, on 19 February 2025, to partially transpose European Directive (EU) 2024/1275 [16].

Tourism buildings, such as youth hostels, are characterized by their intermittent occupancy, diverse energy usage patterns, and varying thermal comfort requirements. These features make energy efficiency improvements particularly challenging but also highly impactful. In addition, the integration of renewable energy sources, such as solar thermal and photovoltaic systems, is crucial for reducing energy dependency and achieving sustainability goals. In the context of tourism, where energy consumption can fluctuate significantly due to seasonal variations and high occupancy rates, implementing renewable energy systems becomes not only an environmental imperative but also a strategic financial investment.

The building sector holds a prominent position in the EU's energy and climate policy due to its significant potential for energy savings and emissions reductions [14], [17] and [18]. Energy consumption throughout a building's life cycle is predominantly linked to operational phases (80–90%) rather than construction phases (10–20%) [19]. Therefore, strategies for decarbonizing the building sector must address both construction and operational efficiency to achieve sustainable outcomes.

The integration of renewable energy technologies in buildings is also strongly supported by EU legislation. The Renewable Energy Directive (RED III) [6] sets binding targets for increasing the share of renewables in the energy mix, including in the building sector. Additionally, the Energy Performance of Buildings Directive (EPBD) [5] encourages the use of renewable energy systems to achieve nearly zero-energy building (NZEB) standards, particularly for new constructions and major renovations.

Despite progress in energy performance standards, around 75% of the existing EU building stock is considered energy inefficient [20]. This inefficiency is partly due to the age of buildings, as around 40% of residential and hospitality buildings were constructed before 1960, a period marked by minimal regulatory requirements [21]. Given that approximately 75–85% of the current building stock is expected to remain in use by 2050 [22], the renovation of existing buildings, including youth hostels, emerges as a critical strategy for meeting long-term energy and climate goals.

In Portugal, the energy consumption pattern diverges slightly from the EU average, with the transport sector leading at 37%, followed by industry (31%) and buildings (29%), split between residential (16%) and service buildings (13%), including hospitality [23]. However, the country has made significant progress in reducing GHG emissions since the peak in 2005, achieving a decrease of approximately 22.5% by 2017 [24].

Given the substantial role of hospitality buildings in energy consumption and GHG emissions, retrofitting older, inefficient buildings remains a priority.

In particular, youth hostels constructed before the introduction of the first thermal regulation in 1991 present a valuable opportunity for energy performance improvements. This study examines the cost-optimal retrofit investment for a youth hostel located in Bragança, Portugal, utilizing dynamic energy simulation and financial analysis to evaluate various energy efficiency and renewable energy measures.

MULTIZONE DYNAMIC SIMULATION

The determination of the BEPI (Building Energy Performance Indicator), based on the multizone dynamic simulation method according to [5] and [15], for the building under study, must be carried out using software accredited under ASHRAE Standard 140, developed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers. These programs are employed for building analysis for various purposes, such as ensuring compliance with energy efficiency regulations, evaluating energy-saving strategies, and performing simulations for sustainable building certification. Such software must, at a minimum, have the capability to model, [15] and [26]:

- More than one thermal zone;
- With an hourly time step over a full calendar year, accounting for 8,760 hours;
- Hourly variation of internal loads, differentiated into occupancy, lighting, and equipment;
- Thermostat setpoints for the thermal zones and HVAC system operation, allowing independent parameterization for weekdays and weekends;
- Heat recovery from exhaust air;
- The thermal mass effect of the building.

The adoption of multizone dynamic simulation in internationally recognized tools (e.g., EnergyPlus) allows the explicit representation of multiple thermal zones, load-building-system interactions, and hourly control strategies, forming the basis for regulatory compliance assessments, energy-saving strategy studies, and sustainable building certification support. The foundational EnergyPlus paper describes the software architecture based on heat and mass balance equations, integration with HVAC system modules, variable time steps (including hourly steps), and the capability to represent phenomena such as system controls, interzone air flow, and building thermal mass effects—features essential for 8,760-hour annual analyses in real buildings [27].

In the European context, the evolution toward hourly methods for the assessment of heating and cooling energy needs—central to EPBD alignment—is well documented in the literature on EN ISO 52016-1. Comparative studies demonstrate the relationship and consistency between the standardized hourly method and detailed dynamic simulations, including the explicit treatment of time-dependent profiles and thermal properties that support year-round hourly analyses [28] and [29].

Hourly modeling of internal loads—differentiated into occupancy, lighting, and equipment—and the parameterization of thermostat setpoints and HVAC operation modes for weekdays versus weekends are critical for accuracy. Literature shows that occupant presence and behavior are stochastic in nature and strongly impact energy use, justifying the application of realistic schedules and stochastic models (e.g., Markov chains). Empirical studies and modeling approaches quantify the sensitivity of results to occupancy schedules and equipment use [30], [31] and [32].

Inclusion of heat recovery from exhaust air (ERV/HRV) in simulations is also well-supported by research. Zhou, Wu, and Wang [33] developed and validated an ERV model within a dynamic simulation environment, showing the influence of setpoint temperatures and climatic conditions on annual energy savings; subsequent studies reinforced these findings through parametric analyses of seasonal ERV/HRV effectiveness under various system configurations [33] and [34].

Finally, correct representation of building thermal mass is recognized as essential in the literature. Classical reviews show its effect in reducing peak loads and smoothing indoor temperature fluctuations, with direct implications for HVAC system sizing and operation when thermal mass is properly modeled in balance equations and hourly discretization [35].

The building energy model was developed using DesignBuilder, a widely used graphical interface for dynamic building simulation that employs EnergyPlus as its calculation engine. DesignBuilder enables the creation of detailed 3D models of the building envelope, internal gains, HVAC systems, lighting, and control strategies, supporting multizone dynamic simulation with hourly time steps over a full calendar year (8,760 hours). This capability allows a detailed representation of thermal zones, internal load schedules, thermostat setpoints (differentiated by weekdays and weekends), HVAC operation, heat recovery, and the thermal mass effect of the building. DesignBuilder is ASHRAE Standard 140 validated, ensuring compliance with international standards for building energy modeling and providing confidence in the reliability of the results [25] and [36].

CASE STUDY

The case study is about a youth hostel located in an inland region in northern Portugal built in 1999 and which is part of a global accommodation network, designed to provide tourist, cultural and social experiences (see Fig. 3).

Fig. 3. Youth hostel building.

Building characteristics

The building has a predominantly rectangular geometry and is oriented towards the north, comprising three floors. The façades combine white-painted masonry on the upper levels with stone cladding on the ground floor, creating a solid base appearance. The eastern section of the site is dedicated to recreational uses, featuring two tennis courts, a small amphitheater, and a landscaped garden. The ground floor accommodates the most functional areas, including administration, dining services, and other support facilities. The upper floors are mainly dedicated to accommodation, with dormitories located on the south side, service areas to the north, and double rooms oriented east–west. Accessibility for people with reduced mobility is ensured by a hydraulic elevator. With a total usable floor area of 2,102.08 m², distributed over 3 floors, Table 1, the hostel is classified as a Large Commercial and Service Building (GES) under Portuguese Decree/Law 101-D/2020 [15].

Table 1. Areas of the building floors.

Floor	Area (m^2)
Floor 0	806,00
Floor 0	760,46
Floor 0	535,62
Total	2102,08

Energy consumption overview

The analysis of the building's energy consumption is essential for understanding its operational efficiency and environmental impact. The hostel's energy use is derived exclusively from electricity, which is critical for all services, and propane gas, which is primarily used for space heating, domestic hot water (DHW) production, and cooking. The building has an annual electricity consumption of approximately 50 MWh and is subject to a four time-of-use tariff, which differentiates between peak, mid-peak, off-peak, and super off-peak hours, each with distinct costs. Figure 1 presents the distribution of electricity consumption across these tariff periods, based on 2023 utility bills, providing insight into seasonal variations and the relative contribution of each period to the total annual demand. A marked increase in electricity use is observed during the winter months, mainly due to greater heating demand, extended use of lighting because of shorter days, and HVAC operation to ensure thermal comfort (see Fig. 4).

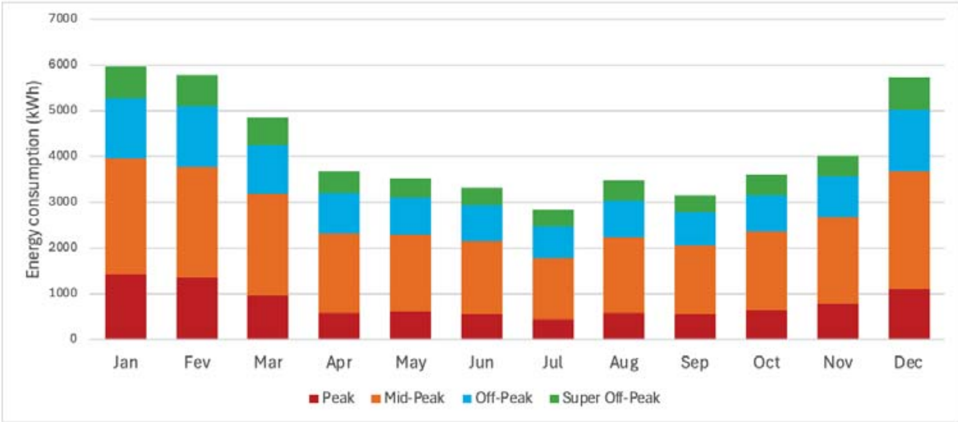

Fig. 4. Annual electricity consumption.

Propane consumption is summarized in Fig. 5. Annual propane gas consumption., which reports a total annual use of 238,257 kWh. It is important to note that the values shown in this figure do not represent regular monthly consumption but rather the deliveries made throughout the year to replenish the external storage tank as needed. Consumption follows a seasonal pattern, with higher demand during winter for heating and DHW production, and lower demand during summer. The combined analysis of electricity and propane data allows for a comprehensive understanding of the hostel's energy needs and supports the identification of opportunities for improving efficiency and reducing operational costs.

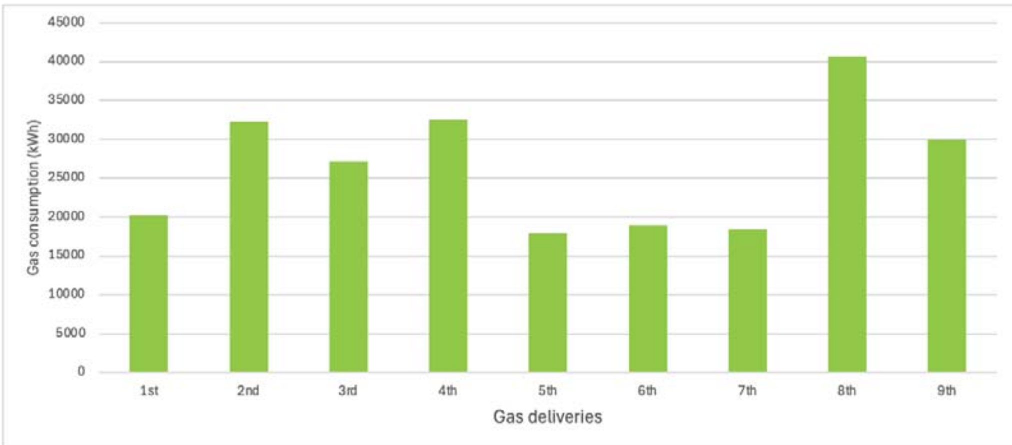

Fig. 5. Annual propane gas consumption.

Climatic zone

The climatic zoning of the country is based on the Nomenclature of Territorial Units for Statistical purposes (NUTS) level III, in accordance with [15]. According to this classification, the building is located in the winter heating climatic zone I3, with a degree-day value of 2,491 °C. For the cooling season, it is situated in zone V2, characterized by an average outdoor temperature of 21.5 °C.

Building occupation

Occupancy density has a direct impact on the building's internal thermal loads. The hostel has a capacity for 88 people and is frequently used by large groups of students, resulting in significant internal gains.

On average, winter occupancy is about 50 people, increasing by approximately 40% in summer. High use of lighting and electronic devices by occupants further contributes to energy demand. A short survey involving 13 occupants was conducted to assess their ventilation preferences. Results showed that over 75% favored natural ventilation, highlighting the importance of air quality and the impact of occupant behavior—such as window opening or shading use—on thermal performance and HVAC efficiency. Periods of high occupancy lead to increased energy demand, while adapting system operation during low-occupancy periods can reduce waste and improve energy efficiency.

Standard schedules were defined in the simulation software to more accurately represent real energy consumption, including system operation, equipment use, and occupancy patterns. Heating systems were programmed to operate only during the winter season, with schedules adjusted according to the severity of the cold: continuous operation on the coldest days, partial daytime operation during mid-winter, and reduced operating hours at the end of the season. Equipment use schedules were based on on-site observations, and occupancy profiles were adapted to reflect daily variations in building use. When fully occupied, the building reaches an occupancy density of approximately 0.042 occupants/m².

Lighting System

A comprehensive inventory of the building's lighting system was carried out to quantify installed power and to evaluate Lighting Power Density (LPD). The survey identified a total of 292 luminaires distributed across all floors, corresponding to an installed power of **3,693 W**. The majority of fixtures are 12 W LED panels (101 units, 1,212 W total) and 9 W A60 bulbs (99 units, 891 W total), complemented by tubular LEDs, GU10 spotlights, decorative ceiling LEDs, and a smaller number of CFL "corn" lamps. This confirms that the building is equipped entirely with efficient LED lighting technology, many of which are fitted with occupancy sensors to minimize unnecessary use.

The detailed distribution of lighting power by space was used to calculate LPD values for each room and aggregated for each floor, Table 2. Results show that most spaces have very low LPD values—typically below 2 W/m²—reflecting the use of efficient LED technology. Higher values are observed in functional areas requiring increased illuminance, such as kitchens, storage rooms, sanitary facilities, and circulation atria. The highest densities occur in the first-floor distribution atrium (**7.54 W/m²**) and the second-floor atrium (**8.35 W/m²**).

Table 2. Lighting Inventory and Installed Power.

Fixture Type	Power (W)	Quantity	Total Power (W)
LED Panel	12	101	1,212
GU10 LED Spotlight	6	11	66
LED Tube 1.2 m	18	7	126
LED Tube 1.5 m	22	34	748
LED A60 Bulb E27	9	99	891
LED CFL "Corn" Bulb	20	10	200
Decorative Ceiling LED	15	30	450
		Total	3,693

Table 3 presents the total installed lighting power and average LPD per floor, resulting in a **global average of 2.17 W/m²**for the building. These results demonstrate that lighting represents a relatively small share of total energy use and internal heat gains, but its contribution is relevant for accurate simulation. The data were implemented in the dynamic simulation model using hourly schedules consistent with occupancy profiles, ensuring realistic representation of lighting loads in the energy performance assessment.

Table 3. Installed Lighting Power and LPD per Floor.

Floor	Installed Power (W)	Total Area (m²)	Average LPD (W/m²)
P0 (Ground Floor)	1,524	753	2.02
P1 (1st Floor)	1,161	589	1.97
P2 (2nd Floor)	1,008	358	2.82
Total	**3,693**	**1,700**	**2.17**

HVAC Systems

Space heating is provided by wall-mounted radiators connected to an 80 kW propane-fired boiler. Burner operation is automatically controlled by a service thermostat and a safety thermostat based on boiler water temperature. Heating is available in bedrooms (1.7–2.5 kW each) and sanitary facilities (0.6–2.5 kW each).

Cooling is provided by ceiling-mounted cassette split units. Thermal load calculations considered the building envelope, orientation, and expected occupancy schedules. Installed capacities are 23 kW (cooling) / 18 kW (heating) for the multipurpose room, 17.4 kW / 17 kW for the dining hall, and 16 kW / 16 kW for the lounge, reception, and lobby areas. Currently, only the units in the multipurpose room and dining hall are operational, and they are switched on only when necessary.

Domestic Hot Water (DHW) System

DHW production is ensured by a dedicated 104 kW boiler, supported by a plate heat exchanger connected to a 2,500 L storage tank. The primary circuit uses a circulation pump and a modulating three-way valve, with temperature sensors controlling water temperature. The secondary circuit includes a dedicated pump managed by a thermostat. The boilers can operate in cascade mode, running sequentially or in parallel to meet seasonal demand more efficiently.

Other Equipment

The building contains various appliances and equipment related to its daily operations, accounting for a total installed capacity of 300.15 kW. However, precise operating schedules for these devices could not be determined, which introduces uncertainty in the estimation of their contribution to total energy consumption.

Building Energy Systems: Installed Power Overview

To accurately represent the energy performance of the building, the installed power of all major systems was surveyed and quantified, Table 4. This includes HVAC (heating and cooling), domestic hot water (DHW) production, lighting, and other electrical equipment. Incorporating these values into the dynamic simulation model allows for a realistic representation of internal heat gains and system loads, supporting a more reliable assessment of the building's overall energy performance and the identification of potential efficiency improvement measures.

Table 4. Installed Lighting Power and LPD per Floor.

System / End-Use	Installed Power (kW)
Heating (HVAC)	131
Cooling (HVAC)	56.4
DHW Production	104
Lighting	3.7
Other Equipment	300.15
Total Installed Power	≈ 545

SIMULATION AND RESULTS

Dynamic simulation is a key technique for analyzing building energy performance, allowing the quantification of potential energy consumption under specific usage and operational conditions. This approach makes it possible to determine heating and cooling demands, as well as internal gains from occupancy and external factors, and is therefore essential for testing alternative design and operational strategies.

Following the collection of all characteristic and energy data, a detailed model of the building was developed in DesignBuilder, incorporating the gathered information to closely replicate real operating conditions and construction features. Fig. 6 shows the 3D model of the youth hostel in DesignBuilder, including the envelope colors, shading elements, and other relevant details, together with the solar diagram indicating the sun's position. This visualization allows the assessment of solar gains and shadowing effects from nearby buildings, which significantly affect the building's energy needs.

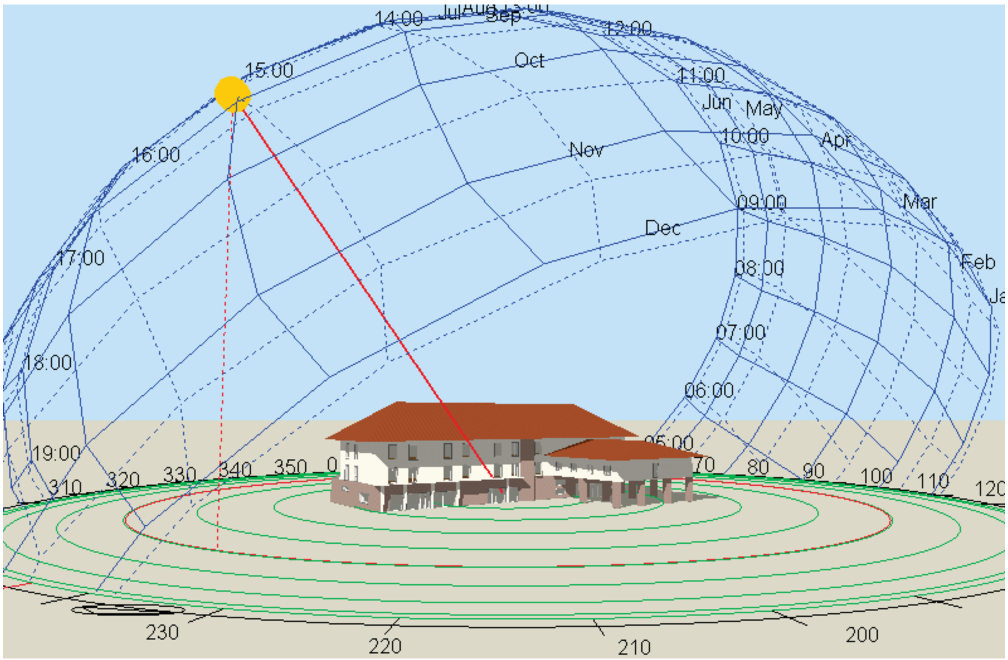

Fig. 6. Youth hostel model created in DesignBuilder, at 3 pm on May 20.

The energy model of the youth hostel was calibrated to ensure that simulated energy consumption closely matched real data. Using 2023 electricity and propane bills as a reference, the model was considered validated when simulated annual consumption deviated by less than ±10% from measured values. The final results showed a difference of –1.5% overall, with electricity consumption underestimated by 3.5% and propane by 1.1%, which falls well within the acceptable tolerance.

The simulation also determined the building's heating needs, resulting in a total required heating capacity of 51.04 kW after applying a safety factor of 1.25, with the ground floor representing nearly half of the demand. The main entrance was identified as the area with the highest heating deficit (5.18 kW), suggesting a potential area for improvement. Cooling needs were not analyzed in detail since several air-conditioning units are non-operational and rarely used.

Internal gains were broken down by source, showing that lighting contributes very little to thermal gains despite significant energy use, mainly due to the efficiency of LED fixtures.

The model also estimated annual CO_2 emissions at 84.21 tonnes, considering emission factors of 0.685 $kgCO_2/kWh$ for electricity and 0.195 $kgCO_2/kWh$ for propane.

DISCUSSION AND ECONOMIC ASSESSMENT

The critical interpretation of the results must be framed within the current Portuguese regulatory context for building energy performance. Decree-Law No. 101-D/2020, later amended by Decree-Law No. 11/2025, establishes the requirements for improving energy performance and regulates the National Energy Certification System (SCE). According to this legislation, the improvement measures proposed in energy certificates must demonstrate technical and economic feasibility, presenting information on investment cost, expected benefits, and payback period. The dynamic simulation approach used in this study provides direct technical support to this legal requirement, allowing the quantification of real consumption patterns and estimating the economic impact of the proposed interventions, in line with the objectives of the SCE and the Portuguese National Energy and Climate Plan 2030 (PNEC 2030).

At European level, the Energy Performance of Buildings Directive (EPBD) — Directive 2010/31/EU and its revision, Directive 2018/844/EU — reinforces the need for buildings to be assessed under realistic operating conditions, favouring hourly calculation methods and calibrated simulation models. The present case study clearly illustrates this principle: the concentration of heating demand on the ground floor highlights failures in air-tightness and envelope performance, aspects explicitly addressed in the minimum performance requirements adopted by Portugal following the transposition of the EPBD. These observations align with the “cost-optimal” principle defined in Commission Delegated Regulation (EU) No 244/2012, which requires Member States to select measures that provide the best balance between investment cost and energy savings, particularly in existing hospitality buildings.

Furthermore, the significant dependency on propane for space heating and domestic hot water (DHW) production contradicts the decarbonisation targets set by both PNEC 2030 and the Long-Term Strategy for Carbon Neutrality 2050 (RNC50), which encourage the gradual replacement of fossil fuels by high-efficiency or renewable-assisted systems. The adoption of air-to-water heat pumps, solar thermal systems for DHW, or photovoltaic systems for self-consumption would be consistent with the Renewable Energy Directive (RED III), which increases binding targets for renewable penetration in buildings and promotes decentralised generation.

The economic analysis carried out within this study also complies with the SCE requirement that qualified experts must indicate technically feasible improvement measures accompanied by cost estimates and payback period. The three selected interventions — replacement of the existing boiler with a condensing boiler (~€16,000), installation of variable-speed circulation pumps (~€4,500), and roof insulation reinforcement (~€14,000) — represent cost-effective actions for service buildings, enabling a predicted reduction of 15–22% in heating demand. The estimated annual savings of €5,500–€7,200 result in a simple payback between 4.5 and 6 years, a value clearly aligned with the economic criteria established in Decree-Law No. 101-D/2020 and the EU cost-optimal framework.

Beyond direct consumption reduction, these measures also contribute to improving the building’s energy certification rating, which is relevant for compliance, market value, and eligibility for national or European funding programmes. When combined with renewable systems — particularly solar thermal for DHW and photovoltaic self-consumption — the building could approach nearly zero-energy building (nZEB) requirements, a central concept of the EPBD and already mandatory for new constructions and major renovations.

Therefore, the combination of dynamic simulation, critical result analysis and economic assessment demonstrates that the proposed measures are not only technically sound but also legally consistent with Portuguese and European energy policy. This confirms the role of simulation as a decision-support tool within the SCE framework and highlights the relevance of energy renovation in hospitality-oriented buildings to meet national and EU-level efficiency and decarbonisation targets.

CONCLUSIONS

This study conducted a comprehensive energy performance assessment of a youth hostel in northern Portugal using multizone dynamic simulation in DesignBuilder/EnergyPlus. The calibrated model demonstrated high reliability, with a deviation below ±10% relative to measured electricity and propane consumption. The results confirmed that heating demand is strongly concentrated on the ground floor, driven by air infiltration and envelope performance limitations, while lighting contributes minimally to internal gains due to the exclusive use of LED technology and occupancy-based controls.

Beyond the technical findings, the study highlights that dynamic simulation is not only a diagnostic tool but also a legally relevant instrument within the Portuguese regulatory framework for building energy certification. In accordance with Decree-Law No. 101-D/2020 and its amendment by Decree-Law No. 11/2025, improvement measures must demonstrate both technical feasibility and economic justification. The simulation outputs provided a quantitative basis for this requirement, enabling the definition of cost-effective interventions aligned with the “cost-optimal” methodology established in EU Regulation 244/2012.

The economic and regulatory analysis shows that relatively simple retrofit measures — such as installing a condensing boiler, variable-speed pumps, and roof insulation — can reduce heating needs by 15–22%, leading to annual savings of €5,500–€7,200 and a payback period between 4.5 and 6 years. When complemented by renewable energy integration, such as solar thermal for DHW or photovoltaic self-consumption, the building could move toward nearly zero-energy building (nZEB) requirements foreseen in the EPBD and supported by the Renewable Energy Directive (RED III). These outcomes reinforce the relevance of retrofitting existing hospitality buildings in meeting national decarbonisation targets under PNEC 2030 and the Long-Term Strategy for Carbon Neutrality 2050 (RNC50).

Future work should expand the analysis to include hybrid and renewable-assisted HVAC solutions, lifecycle environmental impacts, and multi-criteria optimisation of energy performance, comfort, and economic return. Broader application of calibrated dynamic simulation in the Portuguese building certification context could further support decision-making, reduce uncertainties in energy modelling, and accelerate the cost-effective renovation of existing building stock.

Overall, this research demonstrates that dynamic simulation, combined with economic and regulatory assessment, provides a robust and policy-consistent pathway for improving energy efficiency, reducing operational costs, and supporting the decarbonisation of hospitality buildings.

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ANALYSIS OF THE CHARACTERISTICS OF THE AVAILABLE SOLAR RESOURCE AT A FRESNEL PLANT IN EXTREMADURA

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ABSTRACT

This work presents a systematic analysis of solar radiation data measured over four consecutive years (2021-2024) at a Fresnel plant located in Cáceres (Spain). The study aimed to characterize the solar resource available at the facility site and establish objective criteria for the selection of the most appropriate days for subsequent analysis of the system's performance. For this purpose, measurements of direct normal irradiation (DNI) and global horizontal irradiation (GHI) were collected every minute using specific instrumentation (pyrheliometer and pyranometer). Indicators such as accumulated direct radiation, the number of hours with enough radiation for system operation, and radiation variability were calculated. This last parameter proved useful for classifying days according to cloud cover. Only July and August had more than 60% of days with optimal radiation, while the rest of the months had a predominance of days with medium and low radiation. The average annual operating time of the solar plant was 66.6% of the astronomical duration of the day, and 91.6% of the annual radiation was accumulated during this period. The theoretical daily operating time ranged from 4.2 hours in December to 11.4 hours in July. The average annual accumulated radiation was 2030 kWh/m². The variability of the results and the limited number of days with good radiation levels demonstrate the need for extended monitoring periods in order to conduct a realistic analysis of the performance of Fresnel systems.

KEYWORDS

Solar Plant, Linear Fresnel Collector, Solar Radiation.

INTRODUCTION

Concentrating solar technologies constitute a highly interesting option for reducing dependence on fossil fuels in many industrial processes [1]. However, their current level of implementation is still low. Specifically, linear Fresnel collectors offer significant potential for meeting thermal energy requirements in medium and low temperature ranges [2]. Despite this, literature lacks research based on experimental data obtained from real installations subjected to continuous operation over prolonged periods.

In this context, the prototype plant described by Miranda et al. [3], designed for thermal energy generation, has been in continuous operation since its commissioning in 2020. As a result, a comprehensive and representative database was compiled over several years, enabling a detailed analysis of the system's performance under actual operating conditions.

The processing of such a large volume of information requires, as a first step, the classification of the days recorded in order to characterize them appropriately and filter the most relevant data. With this objective in mind, a study of solar radiation levels at the plant site was carried out. Measurements provided by a weather station installed for this purpose were used. The study focused specifically on direct normal irradiation (DNI) and global horizontal irradiation (GHI). Based on these parameters, a criterion was defined for the categorization of days according to the characteristics of the available radiation. Subsequently, the number of hours of radiation useful for the operation of the Fresnel system was evaluated. This variable is of great importance when studying the schedule and seasonality of the industrial processes suitable for the integration of Fresnel technology [1]. Finally, the accumulated radiation corresponding to the different months analyzed was estimated, providing information on the availability of solar resources throughout the year.

MATERIALS AND METHODS

The present study analyzed solar radiation measurements obtained at a Fresnel installation located in southwestern Spain, specifically in the province of Cáceres, Extremadura (latitude 39.646º N; longitude 6.386º W) [3]. Since concentrating solar technologies, including Fresnel collectors, rely on the use of direct normal irradiation (DNI), the analysis focused primarily on this variable. However, it should be noted that the plant's start-up process is controlled based on global horizontal irradiation (GHI), measured by a sensor integrated into the control system, which also makes this parameter relevant for the characterization of the plant's operation.

The weather station used is shown in Fig. 7. It was equipped with a Hukseflux SR11 pyranometer, designed to measure global radiation on a horizontal surface, and a Hukseflux DR15-A1-T1 pyrheliometer, coupled to a two-axis solar tracker (model SunTracker-2000), to measure direct normal radiation. Data acquisition is carried out with a temporal resolution of one minute, which ensures an adequate level of detail for the analysis of the evolution of solar radiation. The monitoring period stretches from 2021 to 2024, providing a set of four consecutive full years of data on the variability and behavior of global and direct solar radiation.

Fig. 7. General view of the direct and global radiation measuring equipment.

In order to quantify the solar energy available at the Fresnel plant site, the daily accumulated direct radiation ($DNI_{accum,d}$) was calculated using Equation (1). In this expression, $DNI_{d,i}$ represents the value of direct radiation corresponding to minute i of day d, while n_d indicates the total number of minutes in which a radiation level higher than 0 W/m² was measured.

$$DNI_{accum,d} = \sum_{i=1}^{n_d} DNI_{d,i} \tag{1}$$

The system operation begins when the global radiation (GHI) exceeds a minimum threshold set at 200 W/m² [3]. Consequently, the direct radiation accumulated during the operating period of the day ($DNI_{accum>200,d}$) was calculated using Equation (2). Likewise, the theoretical operating time of the plant ($t_{200,d}$) was defined as the number of minutes with GHI above the minimum value. The theoretical duration of the day ($t_{theor,d}$) was defined as the interval between sunrise and sunset at the plant site, calculated from the corresponding astronomical equations.

$$DNI_{accum>200,d} = \sum_{i=1}^{t_{200,d}} DNI_{d,i} \tag{2}$$

Besides the daily accumulated solar energy, it's essential to include in the characterization of days a parameter that reflects the stability of radiation. Clouds cause significant fluctuations in the incident solar radiation, which directly affects the plant's performance and continuity of operation. Thus, clear days (considered to be those with optimal operating conditions) can be clearly differentiated because they have low average variability. This approach was previously addressed in the literature, where the selection of sunny days was highlighted [4].

The detection of days with high radiation instability is equally relevant, given that these unfavorable conditions cause frequent interruptions in the system's operation when radiation falls below the required thresholds. For this purpose, the average variation in direct radiation throughout the day ($V_{araver,d}$), defined by Equation (3), was established as a reference metric. This variable was used to classify the successive days analyzed into three different categories: clear days with high DNI, intermediate days, and days with low DNI. The thresholds were selected based on a prior analysis of the radiation curves for different days.

$$Var_{aver,d} = \frac{\sum_{i=1}^{n_d} \left| DNI_{d,i} - DNI_{d,i-1} \right|}{n_d} \tag{3}$$

All these indicators were calculated using experimental solar radiation records provided by the weather station installed at the plant. In addition, the climate database generated by Meteonorm was used. This software provides a typical meteorological year constructed through interpolations from historical series of nearby stations [5]. This dual source of information made it possible to compare the experimental results with representative long-term data, thus reinforcing the classification procedure.

RESULTS

Classification of days

The global and direct radiation records collected at the Fresnel plant during the years 2021-2024 were used as the basis for a systematic classification of days, following the variables defined in previous sections. For each day, the accumulated direct radiation, the average variation of radiation, and the theoretical operating time of the facility were calculated. With these indicators, it was possible to establish objective criteria for selecting representative days, which would be used in the future for a detailed analysis of the Fresnel system's performance, as well as to accurately characterize the site's specific radiation conditions.

In order to classify the different radiation regimes observed at the plant, three reference intervals were established based on a preliminary analysis of the daily radiation curves. First, days with average DNI variation values below 6.5 W/(m²·min) were considered clear days or days with high DNI. Second, intermediate days were identified, with medium DNI conditions, associated with an average variation between 6.5 and 30 W/(m²·min). Finally, days with average variations greater than 30 W/(m²·min) or whose accumulated direct radiation did not reach the threshold of 2 kWh/m² were classified as unfavorable or low DNI days.

Fig. 8 shows three examples corresponding to the month of June. These days were selected because they clearly reflect the situations defined above. Day A corresponds to a scenario of low direct radiation, day B represents an intermediate case with variable conditions, while day C shows a clear day with high DNI levels. The quantitative values associated with each of these days, including the calculated parameters, are summarized in Table 5.

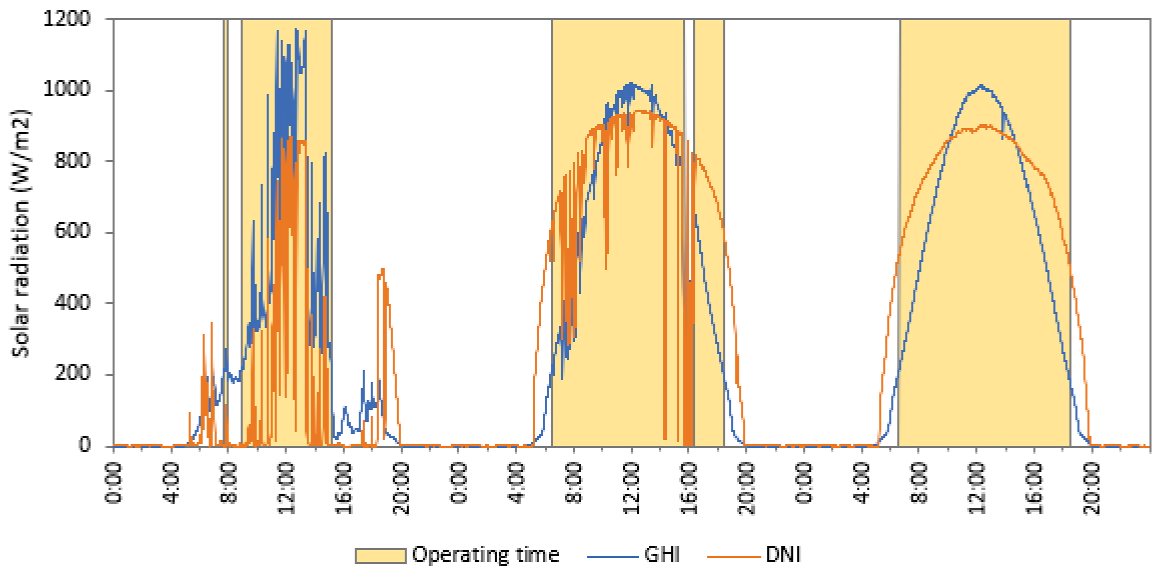

Fig. 8. Operating time and direct and global radiation curves for three days characteristic of the cases described (A, B, and C).

Table 5. Main parameters corresponding to the three selected days.

	$t_{theor,d}$ (h)	$t_{200,d}$ (h)	$\frac{t_{200,d}}{t_{theor,d}}$	$DNI_{accum,d}$ (kWh/m²)	$DNI_{accum>200,d}$ (kWh/ m²)	$Var_{aver,d}$ W/(m²·min)	Classification
Day A	14.81	6.6	44.6 %	2.29	1.72	41.05	Low DNI
Day B	14.78	11.43	77,4 %	10.19	9.2	28.38	Medium DNI
Day C	14.81	11.83	79.9 %	10.29	9.37	2.22	High DNI

Day C was identified as the scenario with the most favorable conditions for the operation of the Fresnel plant. This day had the highest values for both accumulated DNI and time with radiation above 200 W/m², which represented about 80% of the theoretical duration of the day. Likewise, the variability of direct radiation was minimal, with a value of $V_{araver,d}$ below the threshold of 6.5 W/(m²·min), confirming the radiative stability characteristic of a clear day.

Day B, on the other hand, had intermediate conditions: cloud cover was clearly identifiable due to the increase in the average variation in radiation (28.38 compared to 2.22 W/(m²·min) on day C). Although the reduction in accumulated radiation was relatively low (less than 2%), radiative instability would have had a significant effect on the operation of the system, to the point of causing a shutdown of the plant at the end of the day, as shown in Fig. 8.

In contrast, day A represents a scenario that is not appropriate for the evaluation of the facility's performance. The average variation in direct radiation exceeded the threshold of 30 W/(m²·min) and the cumulative radiation was around 80% lower than the value reported on day C. Furthermore, the effective operating time of the plant did not even reach 45% of the theoretical period available, highlighting the low quality of radiation on this day.

Fig. 9 summarizes the monthly distribution of the percentage of days classified in each category (high, medium, and low radiation) during the four years considered. The results show that only July and August exceeded 60% of days with optimal conditions, along with almost 30% of days with intermediate radiation levels. In the other months, however, the proportion of days with low radiation was dominant, ranging from 45% to 61%. In March, coinciding with a particularly rainy period in the years analyzed, this percentage increased to 67%.

Overall, the results show that the availability of favorable days for the operation of the Fresnel system is relatively limited at the site studied. For this reason, it is essential to achieve a prolonged period of operation with a sufficient number of valid days, which is a necessary condition for carrying out a reliable assessment of the long-term performance of the facility.

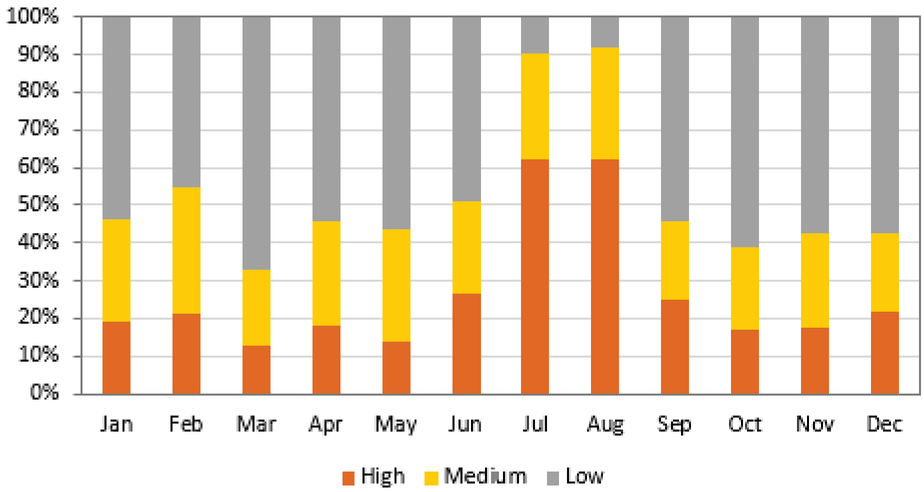

Fig. 9. Percentage of days in each month that belong to the three defined radiation categories.

Theoretical average operating time of the solar plant

The radiation values were also used to estimate the expected average operating time of the Fresnel plant. Fig. 10 shows the monthly average of expected daily operating hours based on the available radiation conditions. When comparing both sources of information used, it can be seen that the values from the weather station were 4.9% lower than those obtained from the typical meteorological year generated by Meteonorm. This difference is partly related to the fact that the measurements cover a period of only four years, so they could be affected by the year-to-year variability of weather conditions and not fully reflect the long-term climate behavior of the area. Furthermore, it should be noted that Meteonorm is based on interpolations of historical data from nearby stations and provides hourly results, while the local station offers measurements with higher temporal resolution, with records taken every minute.

According to the experimental meteorological data, the average daily operating time of the plant ranged from 4.2 hours in December to 11.4 hours in July. If the analysis is restricted solely to days with high DNI, the values increase to 6.4 hours in December and 11.8 hours in June, highlighting the strong dependence of operating time on the meteorological conditions at the site. These results correspond to the forecast based on average radiation levels. The occurrence of possible failures in the solar plant can cause interruptions in the operation of the system, reducing the effective working time.

When the operating time is related to the theoretical length of the day (from sunrise to sunset), experimental measurements give an annual average percentage of 66.6%, compared to the 70% estimated with Meteonorm. These values are consistent with the results reported by Fadhel et al. in their analysis of a small-scale Fresnel collector in Tunisia, where an operating fraction of close to 70% was documented [6]. Famiglietti et al. also estimated the hours of operation at a solar plant in Madrid (Spain), observing a decrease in operating time during the winter months and a total of 2060 hours of operation per year according to their criteria [7]. In the present study, the fraction varied between a minimum of 45.6% in December and a maximum of 79% in August, with 2916.1 hours of operation during the entire year.

Fig. 10 also includes the distribution of operating hours according to radiation levels. It can be seen that 84.9% of the hours in which GHI exceeded 200 W/m² coincided with DNI values also above this threshold, reaching 97% in July and August. In addition, 74.8% of the operating hours corresponded to conditions with DNI above 500 W/m², while 41.5% even exceeded 800 W/m², highlighting the plant's potential to operate under favorable radiation conditions.

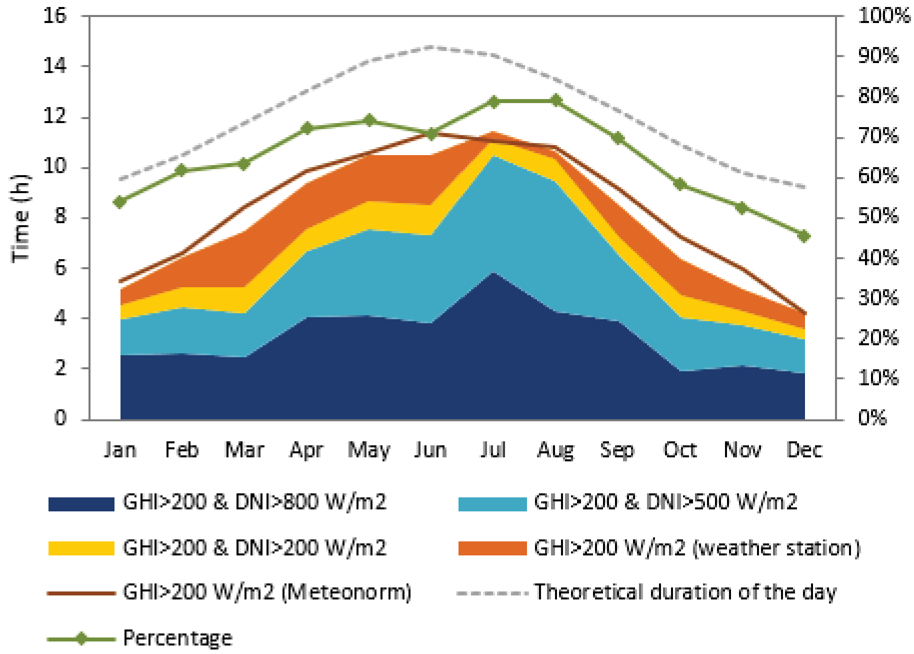

Fig. 10. Average number of hours per day according to the solar radiation level.

Accumulated radiation levels

Fig. 11 shows the monthly values of accumulated DNI obtained from the records of the weather station for the period 2021-2024. In addition, the monthly average values corresponding to the analysis interval, the estimates generated using the Meteonorm software, and the radiation accumulated only during the intervals in which the GHI exceeded 200 W/m² are included.

The results reflect significant annual variability. In the most unfavorable case, corresponding to December 2023, accumulated radiation reached a minimum of 63.5 kWh/m², while at its maximum, registered in July of the same year, it reached 296.4 kWh/m². The average annual value of cumulative direct radiation stood at 2030 kWh/m², with a moderate year-on-year variation of around 2.6%. The comparison with Meteonorm shows good agreement, as the latter yielded a very similar value of 2058 kWh/m².

It should be noted that Bellos et al. proposed the concept of "effective duration of the day," defined as 80% of the interval between sunrise and sunset, and demonstrated that approximately 96% of incident solar energy was captured during this period [8]. In the present analysis, when considering the theoretical operating time of the plant (whose annual average is equivalent to 66.6% of the astronomical duration of the day, as described above), the accumulated direct radiation represented 91.6% of the total annual solar energy, which shows a high degree of utilization of the available irradiation within the useful hours of operation. Famiglietti et al. estimated that the loss during shutdown hours was 14% of the overall amount of energy available [7].

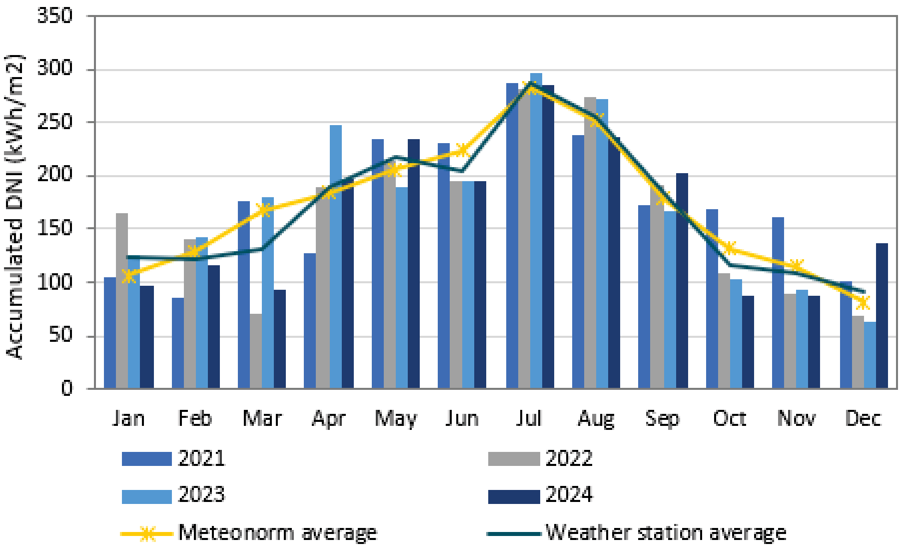

Fig. 11. Average daily accumulated radiation over the four years analyzed.

CONCLUSIONS

The analysis of four years of solar radiation measurements at a Fresnel plant in Spain provided a detailed characterization of the availability of solar resources at the site. In addition, a systematic procedure was established to classify days according to radiation conditions and select the most representative dates for future analysis of the facility.

A clear and objective criterion was established to identify solar radiation conditions based on the average variation in DNI levels. Days with a variation below the threshold of 6.5 W/(m²·min) were cloud-free and maximized the plant's operating time and accumulated solar radiation, allowing for optimal use of the Fresnel system. However, the results showed marked seasonal variability: while in July and August more than 60% of days had optimal radiation conditions and 30% had average levels, low radiation prevailed in the remaining months (up to 67% in March).

66.6% of the hours in the year had radiation values above the minimum level for the plant to operate (200 W/m²), ranging from 45.6% in December to 79% in August. These hours accumulated 91.6% of the direct radiation for the year, which was around 2030 kWh/m². This data is consistent with the estimates of the Meteonorm software (2058 kWh/m²), which reinforces the reliability of the data.

The average daily operating time ranged from 4.2 hours in December to 11.4 hours in July, increasing to 6.4 hours and 11.8 hours when only days with high DNI are considered.

These findings show that the availability of days with optimal direct solar radiation conditions is limited despite the good levels of accumulated radiation at the prototype location. This demonstrates the need to monitor the plant's operation over extended periods to ensure sufficient favorable days to evaluate the performance of Fresnel systems under real conditions and to properly scale their operation in industrial processes dependent on solar thermal energy.

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Hydrogen Injection into the Brazilian Gas Network: A Review of Feasibility and Challenges

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ABSTRACT

The energy transition toward a low-carbon economy demands solutions that balance sustainability, economic viability, and supply security. In this context, low-carbon hydrogen (LCH) emerges as a strategic alternative to natural gas, especially through blending, which allows for its gradual introduction by leveraging existing infrastructure. This article analyzes the technical and economic feasibility and regulatory challenges of injecting H_2 into Brazilian gas grids, based on a review of academic literature and institutional documents published between 2019 and 2025. The results indicate that blending can reduce emissions associated with natural gas by up to 20% but still faces barriers related to cost, efficiency, and operational safety. Three infrastructure adaptation scenarios are identified: use of the current network, construction of new pipelines, or the inclusion of inhibitors, each with different impacts on CAPEX and OPEX. The legal framework has advanced with the enactment of Law No. 14,948/2024, which establishes the National Low-Carbon Hydrogen Policy; however, its effectiveness will depend on clear regulation and well-articulated institutional coordination. It is concluded that Brazil has favorable conditions to integrate LCH into the energy matrix, but success will depend on pilot tests, financial incentives, and consistent regulatory strategies.

KEYWORDS

Low Carbon Hydrogen, Blending, Natural Gas, Economic and Financial Feasibility, Energy Transition.

FROM LITERATURE AND PATENT ANALYSIS UNDER THE EESG PERSPECTIVE

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ABSTRACT

This study provides an integrated technological foresight analysis of low-carbon hydrogen, combining a literature review with patentometric analysis within the Environmental, Economic, Social, and Governance (EESG) framework. Analyzing 130 patent families using Orbit Intelligence (Questel) software, the study identifies key technological trends, innovation actors, and strategic collaborations. The results show a sharp rise in patent filings from 2020 onward, with dominance in electrical and chemical engineering fields and a strong presence of Chinese institutions. Based on these insights, a technological roadmap was created, divided into three phases (2020–2040) that link technological development with sustainability goals. The research highlights innovation bottlenecks, governance challenges, and opportunities for diversification, offering valuable support for decision-making in research, policy, and industry amid the global energy transition.

KEYWORDS: low-carbon hydrogen, patent analysis, technological roadmap, sustainability, EESG.

BIBLIOMETRIC ANALYSIS OF Municipal Solid Waste Management IN BIOREFINERIES UNDER EESG PERSPECTIVE.

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ABSTRACT

This article aims to investigate how academic literature has addressed the management of Municipal Solid Waste from the Economic, Environmental, Social and Governance - EESG perspective, identifying research gaps and contributions applied to sustainability regarding the use of these wastes.

Using the Scopus database, a bibliometric analysis was conducted using the PRISMA method, with the assistance of VOSviewer. A total of 1,044 articles were analyzed in four EESG clusters. The results show a strong academic output in the economic and environmental clusters, while the social cluster still has little focus on issues pertinent to this theme, with China, India, and the USA leading. However, governance remains underexplored. The results indicate that, although the principles of ESG are indirectly present in current research, with an increase mainly in the Environmental aspect, there is a lack of focus, especially in Governance. Leaving clear the importance of studying each cluster that highlighted the research gaps. It was also possible to observe an increase in research in the economic area, being practically the same as in the social area , which did not have a significant increase like in the environmental cluster. The study highlights the need for multidisciplinary approaches and how the cluster study method further helps to extract the best from each area, especially the parts that need more attention to implement effective strategies in MSW biorefineries (Ecoparks).

KEYWORDS

Municipal Solid Waste, Biorefineries, Ecopark, EESG.

1. INTRODUCTION

The most relevant and urgent topic currently is climate change and possible actions to mitigate it. The discussion has been recurring and extensive among countries since it was one of the main agendas of both the G20 meeting main forum for international economic cooperation, composed of the nineteen largest economies in the world plus the African Union and the European Union, the last one was held in November 2024. It is also on the agenda of the BRICS Meeting, an economic and political bloc composed of emerging countries, with the latest edition held in July 2025 in Rio de Janeiro, in addition to the increasing importance of the UN Climate Change Conference, with the latest being COP 30 in Brazil in November 2025.

In Hoornweg [3], the expectation is that the global volume of waste will increase from 2.01 billion tons to 3.4 billion tons by 2050. Emissions related to solid waste are expected to increase to 2.38 billion tons of CO_2 equivalent per year by 2050, if there are no improvements in this sector [2]. It is estimated that the global peak in waste production will be reached around 2100, although in the mid-century for developed economies, aggressive waste reduction strategies may be able to reduce waste generation by about 30%, reaching the peak in 2075 [3]. According to the 2023 Solid Waste Overview in Brazil by ABREMA [4], these wastes are classified as construction and demolition waste, agricultural waste, industrial waste, healthcare service waste, in addition to Municipal Solid Waste (MSW), which has a very large generation volume. In Brazil alone, more than 221 thousand tons of waste were generated every day, about 382 kg of MSW per inhabitant, with an estimated total of approximately eighty-one million tons of MSW in the year 2023 [4].

The increase in solid waste generation constitutes a growing challenge, both in Brazil and around the world. The projections point to the urgency of measures to reduce the effects of this increase, making the transition to circular economy models and the adoption of efficient waste management policies fundamental to ensuring a sustainable future.

According to Peng [5], the best way to dispose of and add value to waste to meet the growing global population and the increasing volume of MSW is through the conversion of waste into energy (biorefineries). These plants are facilities that integrate various processing technologies to convert MSW into valuable products and energy, being especially important for the reduction and transformation of these materials on the global stage [5]. According to Chin [6], there are specialized MSW energy plants known as "waste eco-parks (WEP)," or Industrial Eco-parks, which integrate MSW management facilities based on the principles of the circular economy and energy transition, establishing closed-loop systems for MSW materials within a specific planned area [6], being an important tool for replacing landfills.

For changes in waste treatment to occur, research and planning are necessary, which are made possible through EESG analysis, which facilitates the interpretation of the overall scenario and verifies the needs of each area (Economic, Environmental, Social, and Governance). This method has more robust indicators and multi-criteria assessment tools that are important for guiding political, academic, and business decisions, especially in complex systems like biorefineries [7]. This being instruction provides a comprehensive view with all the points involved in a holistic analysis model that has been widely used [8]. With the ability to provide solid indicators, this evaluation method directly contributes to strengthening climate change mitigation strategies and creating a sustainable economy.

Thus, the objective of this article is to verify how research on Municipal Solid Waste Management (MSWM) and other bioproducts is focused on the application of ESG, what the main topics and authors are, as well as the collaborations that have been occurring. Using the Scopus database, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) research method was applied, and a bibliometric analysis with the support of the VOSviewer software was conducted, separating the search by cluster, making it more extensive due to the need for sectorization. In this way, it will be possible to understand how EESG is being developed, allowing the discovery of the flaws in this method and making it possible, based on this bibliographic data, to analyze the applicability of EESG and develop better practices in the implementation of Industrial Ecoparks.

2. METHODOLOGY

The methodology applied was through a bibliometric analysis using the PRISMA method (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) to obtain an overview and analyze the evolution of scientific research on the discussed topic [9]. The chosen database was Scopus due to its relevance to the topic and the indexing of journals with a significant impact factor within the subject studied.

The criteria defined for the search were documents in English, from the last five years, and only scientific articles and reviews. The search terms were divided into four clusters according to the EESG and an additional four keywords for each, chosen based on the greatest relevance each brings to its cluster, totaling sixteen searches in the database [7]. This subdivision of keywords was necessary precisely to define the main topics addressed in each part of the EESG and to identify the gaps that are not being studied. All searches had the search string TITLE-ABS-KEY(("eco-park") OR ("eco-industrial park") OR ("Municipal solid waste") OR ("MSW")) as the basis combined with the others, as shown in Figure 1.

. The searches conducted on 06/12/2024 found 1133 articles, and after filtering, eighty-nine of these were found to be duplicates (using Mendeley), resulting in a total of 1044 documents (Figure 1). These data were submitted to the VOSviewer software, which returned spreadsheets and a word cloud for detailed bibliometric analysis, with a total of articles analyzed by clusters: 270 Economic, 491 Environment, 273 Social, and 10 Governance.

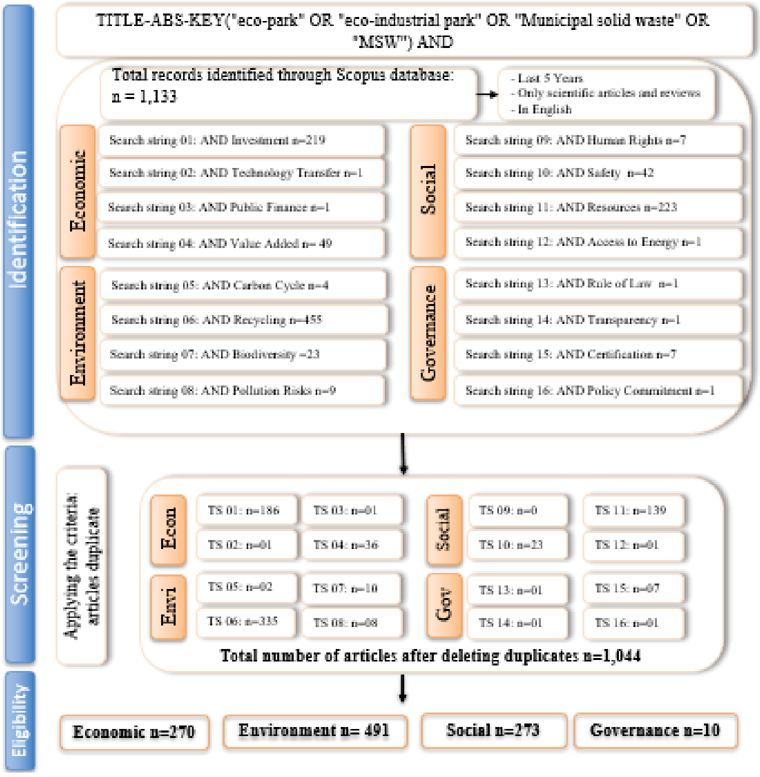


Fig. 12. PRISMA Flow Diagram (Author, 2025)

3. RESULTS AND DISCUSSION

3.1. Bibliometric Analysis

The following presents the Bibliometric Analysis of the 1044 articles found in the database according to the predefined search, as well as the academic production on these subjects in relation to region, authors, collaborations, and topics interconnected with the main ones. The paper is divided into clusters, which are Economic, Environment, Social, and Governance, and presents the main results of the analyses conducted in VOSviewer. These interpretations, organized by cluster, offer an integrated and multidimensional view of bibliometric analysis, allowing us to understand how each dimension contributes to sustainability in MSWM. An important detail, the Governance section had its analysis limited to the main authors and publication locations due to its scarce contribution and lack of collaboration between countries in the articles found.

3.1.1 Cluster Economic

Figure 02, presents the interaction of countries in relation to the amount of joint production (in this case, at least five published documents), it is evident that China has the highest production with sixty-nine documents, forty-three of which are with thirteen countries and a total of 2381 citations, with greater cooperation in these works with India (six documents) and the United States (six documents), which are in 4th place in production regarding the economic part of the EESG. India is in second place with thirty-three articles and 1817 citations, of which twenty-nine are co-authored with the other thirteen countries, including research with Brazil. This one, which is in third place (the best position in academic production compared to the other clusters), has twenty-six published documents, 639 citations, and seven partner countries with ten of these documents. A country that had no interaction with the others was Russia, with five publications in the area (not shown in the illustration). This indicates a greater pursuit by China in terms of scientific novelty, given that the Economic aspect in this type of analysis is recent and that Brazil is increasingly seeking to establish itself in the scientific arena, and in this case, has produced a significant amount of research in the economically sustainable area compared to other academic powers.

Among the publications, some authors who had more relevance are mentioned, one example is Dan Cudjoe who has 224 citations distributed across six publications, all produced in China and in high-impact journals such as "Sustainable Production and Consumption" and "Energy." It is worth noting that Heng Chen and Gang Xu together have 163 citations because all six documents were co-authored and in partnership with various other authors. A single publication by Sharma from 2021 has 282 citations, "Circular economy approach in solid waste management system to achieve UN-SDGs: Solutions for post-COVID recovery"[10] precisely addresses the impact the pandemic had on the evolution of MSWM to achieve the Sustainable Development Goals (SDGs), showing that the articles are in line with the sought-after theme and bring important reflections.

In addition to this information, it was possible to find through the VOSviewer analysis the most cited materials in the references of the papers (called co-citation) within the 270 in the Economic section. The book "What a Waste 2.0: a global snapshot of solid waste management to 2050" by Kaza S. et al. [2], published in 2018, had seventeen citations, and "What a Waste: A Global Review of Solid Waste Management" by Hoornweg D. and Bhada-tata P. from 2012 [11] had eight citations. Both discuss waste management, with the first having over seven thousand citations and the second having over five thousand citations according to Google Scholar. Another important piece of information is that the main authors have also been cited as references in other works, such as Dan Cudjoe with a 2021 paper "Forecasting the potential and economic feasibility of power generation using biogas from food waste in Ghana: Evidence from Accra and Kumasi," [12] cited four times, which also discusses the use of waste, now as a source of energy for biogas production. This was a recurring theme among the analyzed works and demonstrates a continuous and recent discussion. Another example is from Heng Chen, who had two different works: "An innovative waste-to-energy system integrated with a coal-fired power plant" [13] and "Municipal Solid Waste (MSW) as a renewable source of energy: current and future practices in China," [14] cited eight and four times each (the first one had the participation of Gang Xu).

Figure 03 illustrates the main keywords with hundred occurrences or more are 'municipal solid waste' (225), 'investment' (156), 'economic analysis' (117), and 'solid waste management' (100), presenting a division of themes related to the economic part, but without losing focus on waste management. According to VOSviewer, they are grouped in diverse ways due to the nature of the theme or specific research line (identified by different colors), with the first three distributed in green and the last being the main one in red. The size of the circles also indicates the number of documents. Themes related to technology transfer, economic growth, investments, operational costs, and waste valorization are highlighted. The energy transition and the pursuit of economic efficiency stand out as crucial points where this combination of words refers to the proposal of this cluster, highlighting the greater search for forms of investment and research in the area of waste management.

Thus, innovation, technology transfer, and support with economic incentives are fundamental for a sustainable transition, which according to Pandey [15] is best defined through the term "innovation cooperation" with a group of people more involved in the pursuit of Sustainable Development for all. Strategic investments not only drive economic development but also reduce environmental impacts and strengthen the sustainability of the sector.

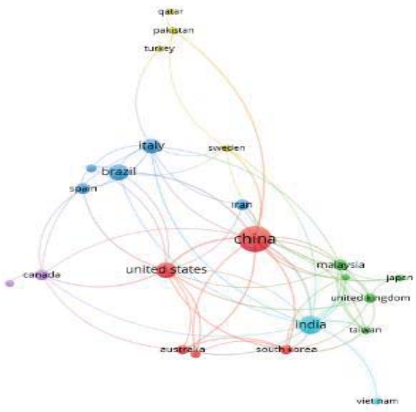


Fig. 2. Co-participation of Countries (ECON)

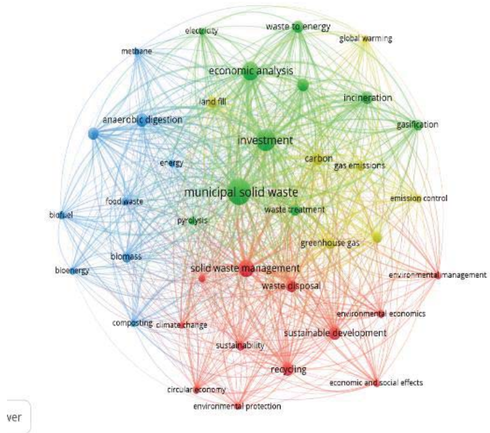


Fig. 3. Word Cloud (ECON)

3.1.2 Cluster Environment

In this cluster, as in the previous one, China also leads with the highest number of documents produced, ninety-six with 3070 citations. However, unlike the economic sector, India has a higher number of citations (3332) among these studied documents, totaling eighty. What presented a considerable difference compared to the previous one was Brazil's position with twenty-one publications in seventh place, but with a significant difference when analyzing the citations, with 210 citations placing it in 37th position. Once again, China is the main researcher due to the significant internal incentive for research, making it possible to affirm that India is the largest reference in this segment due to the high number of citations. There is a significant difference in the total volume of publications when the environmental aspect of EESG is considered, with a possible cause being the recent inclusion of the E for Economy in the term [16]. It is not possible to affirm this, as there was no in-depth analysis to identify whether these works were directed towards sustainable development or not.

In Figure 04, the connection between the countries that collaborated on research (illustrated by countries with at least eight documents produced) is presented. Thus, China's largest research partner was the United States, with eight out of the forty-three works produced together, and sixteen other partner countries, including Brazil, which had only one participation. This one had seven articles produced in partnership with six countries, including the United States (02) and Portugal (01). Thus, bringing an important piece of data to evaluate how the variety of countries through universities and academic research are contributing to technological transfer and not being restricted to a select group.

The main authors of this cluster are Sunita Varjani has five documents with a total of 617 citations, two published in 'Science of the Total Environment' and two in 'Bioengineered', and the author Ashok Pandey has four documents but has been cited more frequently, 805 times. It is important to highlight that among these citations, there is a work that Varjani and Pandey produced together (498 times cited). However, the authors with the most publications are not among the most cited works, as is the case with the article "The Relevance of Circular Economy Practices to the Sustainable Development Goals" by Schroeder (2019), published in the Journal of Industrial Ecology [17], a journal with a relatively minimal impact factor of 5.4. Nevertheless, the work was cited 1001 times and presents a systematic review on the relationship between Circular Economy practices and the implementation of the SDGs. It is important to highlight that the specialists in the field or those most frequently cited on the topic are not being referenced in other works, indicating a fragmentation of knowledge since the theme has been widely studied.

In the co-citation presented by VOSviewer of the articles in the Environment section in the EESG analysis, the most referenced documents in the works of this bibliographic search are exactly the same documents as in the previous cluster (Economic): the book "What a Waste 2.0: a global snapshot of solid waste management to 2050" [2] with twenty-three mentions and the article "What a Waste: A Global Review of Solid Waste Management" [11], seventeen times. What represents a theoretical foundation of the gathered articles focused on the main theme, which is exclusion and its management, considering that EESG analysis significantly contributes to this.

Through figure 05, the occurrence of themes related to the environmental part is observed, which appeared at least twenty-six times, totaling forty different forms, already excluding the repeated/similar ones and those out of context. The four main keywords were 'municipal solid waste' (416), 'recycling' (292), 'solid waste management' (271), and 'waste disposal' (111), all with more than one hundred mentions. According to the software, these words are the most connected, meaning they are frequently presented together in the same articles or bibliography. Analyzing these terms, the emphasis is not only on the conservation of natural resources and the protection of biodiversity, but also on finding ways to do so sustainably and with returns in various areas.

By doing so, a strong connection is made with the ECON cluster, as effective environmental practices are also associated with economic efficiency and long-term cost reduction. According to Peng [5], efficient solid waste management and waste valorization are essential for mitigating environmental impacts.

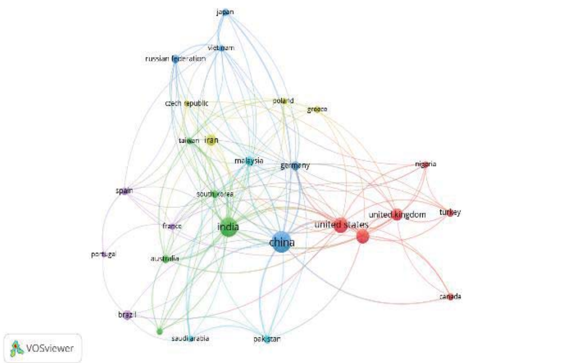


Fig. 4. Co-participation of Countries (ENVI)

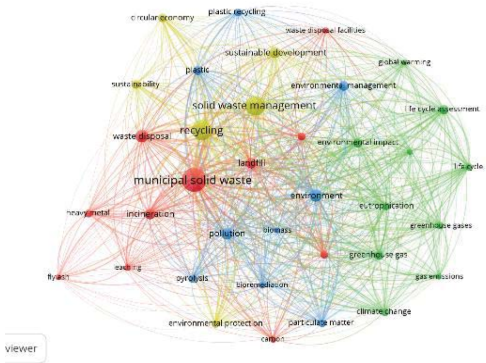


Fig. 5. Word Cloud (ENVI)

3.1.3 Cluster Social

At this stage, the data from the search related to the Social aspect is presented, figure 06 shows the interaction between the countries regarding their publications, in this case, it is not possible to determine which country publishes the most as there is not a significant difference between China and the USA, the countries respectively have 59 and 56 documents. In the case of China, out of these fifty-nine documents, twenty were in partnership with eleven other countries, totaling 1444 citations, in addition to three publications with the USA. Regarding this country, there is a significant disparity compared to China; it has almost 1/3 of the total, 534 citations. Of the documents produced by the United States, twelve were with other ten locations. Brazil is in fourth place with twenty documents (falling to 20th in terms of citations, 164 times), two of these in collaboration with Portugal, two with Spain, and only one with Italy. It becomes evident then that the cooperation between the countries is practically the same, however, the citation defines a dominant as a theoretical reference, once again China stands out just like in the first cluster.

When the analysis is about the authors, two authors stand out with three documents (Ming-Lang Tseng and Jinping Tian) and besides Ming-Lang Tseng with 170 total citations, three others had 148 citations in their works. Articles that were co-authored among the top four authors demonstrate that there is collaboration among these researchers, and in this case, there is no analysis to be made of these professionals. Regarding the citation of each work, in this case in the Social part of the EESG, "Soil salinity under climate change: Challenges for sustainable agriculture and food security" (2021) by Ra Mukhopadhyay [18] has 365 citations. Unfortunately, when analyzed qualitatively, it did not present the characteristics sought in this review, as the objective of this article is to inform about soil salinity in situations of climate change. This highlights that in addition to quantitative analysis, qualitative analysis is extremely important, as even this document returned from a search that had keywords such as 'eco-park', 'eco-industrial park', 'Municipal solid waste', 'MSW', 'Social', and 'Resources'. Checking the second most discussed, it was published in the journal 'Journal of Hazardous Materials' by Zhang Yuying (2021) and had 352 mentions up to the date of data collection. "Treatment of municipal solid waste incineration fly ash: State-of-the-art technologies and future perspectives" [19] deals with the analysis of technologies to mitigate fly ash in MSW incineration to maximize environmental, social, and economic benefits.

Another piece of data previously mentioned is the most referenced works in this database; in this case, they were the same documents already cited, demonstrating a structured study base and how important these documents are in the study of waste (What a Waste 2.0: a global snapshot of solid waste management to 2050 [2] with seven mentions and the article What a Waste: A Global Review of Solid Waste Management with nine [11]). Having a difference: the document "Educational Policy and Accreditation Standards for Baccalaureate and Master’s Social" that discusses the guidelines for Bachelor's and Master's in Social Work had eight citations. This reveals a problem with the search filter, as the acronym MSW in the social context means 'Master’s Social Work,' thus having a double meaning and altering the result when searching with this term and its specific meaning for this research.

The last topic is the analysis of keywords that maps how the subject is being addressed, and thus we have among the terms, at least sixteen times cited, twenty-two words. The main ones are 'municipal solid waste' (164), 'solid waste management' (106), 'economic and social effects' (72), and 'sustainable development' (66), showing the same trend as the other divisions with a focus on the sustainable part, where the main theme remains waste and solid waste management, but in this case, there is also a concern with social effects in addition to economic ones (figure 07). Making it clear the need for specialized research when it is necessary to talk about the social aspect of EESG since the other topics did not give due attention to this part. Thus, waste management aimed at producing clean energy is seen as a vector to also improve social conditions and promote a just transition [7]. The keyword 'social work education' was related by the software with sixteen mentions, but with no links to the others, corroborating the previously mentioned incorrect data collection regarding the Master's in Social Work.

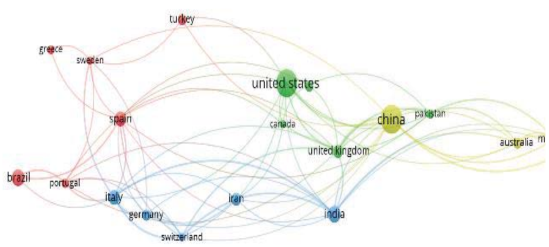


Fig. 6. Co-participation of Countries (SOCIAL)

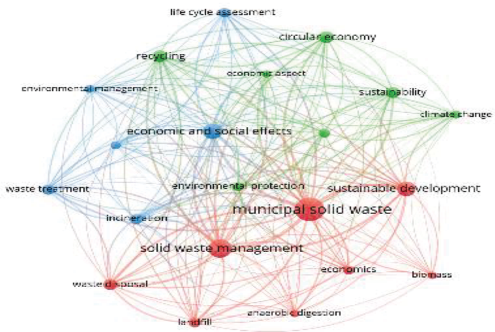


Fig. 7. Word Cloud (SOCIAL)

3.1.4 Cluster Governance

Due to the exceptionally small number of articles found in the search (only ten documents), it is not possible to conduct an in-depth bibliographic analysis, highlighting the research gap. The main points to highlight are the works done and the authors who produced them. The most cited work with thirty-one mentions is "Boosting Degradation of Biodegradable Polymers" from 2023, authored by Anibal Bher, Yujung Cho, Rafael Auras, [20] produced by the USA (they published one more on this topic).

Unlike the other clusters, China only has one work with twenty-two citations (“Bayesian-based NIMBY crisis transformation path discovery for municipal solid waste incineration” in China from 2019 [21]). Now, we have Portugal's production with a total of two articles and sixteen citations, one of which is in partnership with Brazil: "Quality standards for urban waste composts: The need for biological effect data" [22], by authors Sónia Chelinho, Carla Pereira, Patrik Breitenbach, Dilmar Baretta and José Paulo Sousa.

Among the works, only six are related to the central theme (Solid Waste), and of these, only two report a theme on public policies, one being Brazil's participation and the other being "Towards flexible evaluation schemes in areas with lacking information: a case of waste governance in Mexico" [23], which evaluates governance in local waste management systems in Mexico and seeks to verify the effects of the European Union's Circular Economy Package concerning MSW. The last data presented is about the keywords, which totaled six: 'municipal solid waste', 'solid waste management', 'certification', 'circular economy', 'composting', and 'sustainable development'. These are quite like those of the other clusters, except for Certification, which has only two occurrences and is the only one linked to the Governance cluster.

3.2. Analytics and Discussion

3.2.1 Conclusions on the bibliometric data

Thus, the above results not only describe the current state of research in the field but also allow for a critical reflection on how much practices and scientific production have evolved to address contemporary challenges of sustainability and environmental management. This interpretation provides a solid foundation for the discussion of the results in its bibliographic analysis.

Thus, the variations in the number of publications and citations over time generally indicate a progressive growth in scientific production (figure 8), suggesting that the topic has gained greater relevance in the academic field and among MSWM professionals, except for the Governance aspect, which is still much lower in the number of publications, not ruling out that this topic has been discussed in articles but that documents specifically focused on this theme do not appear. This increase in documents can be associated with greater awareness of sustainability and the emergence of environmental policies, impacting both academic production and management practices.

Through the graph in figure 9, it is possible to see how each of the main countries producing in this area is focusing their research, highlighting the importance of dividing this search by cluster, where this data provides us with a perspective on the concentration of applications. According to the International Renewable Energy Agency IRENA (2022), the China has a greater absolute production in the economic area, even though it is not its main research focus, as is the case with the environmental sector, which may be a possible reflection of a more active policy in recent years and its central role in the clean technology market and neutrality goals [25].

Another point is the difference between the clusters in the number of total citations and publications on the subject, which can be interpreted as an indication of studies with a greater impact in the environmental field. The diversity of the authors and institutions involved also points to a multidisciplinary and collaborative approach, enriching bibliometric analysis. The high index of co-authorships among countries highlights important partnerships and collaboration networks so that the challenges in these areas can achieve even more significant success with researchers collectively contributing to the advancement of knowledge on MSWM.

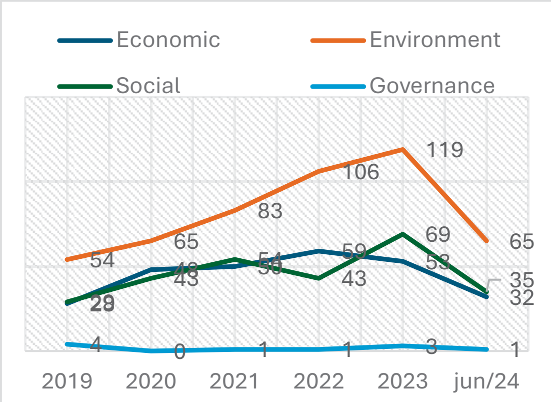
3.2.2 About the main references

The reports "What a Waste 2.0" with a global scope and a projection from 2016-2050 (World Bank, 2018), as well as "Panorama ABREMA 2023" which has a national scope with data from 2023, reveal exponential growth in urban solid waste. The first stands out as the most comprehensive global assessment of solid waste, with data from 217 countries and projecting waste generation trends until 2050. This report consolidates official national statistics, municipal records, and modeled estimates for regions with limited data availability, but it heavily relies on modeled data for low-income countries, where municipal reports are incomplete or inconsistent. The second is also prepared based on municipal reports and sectoral surveys. It offers detailed information on the composition of waste, collection coverage, and treatment routes, serving as the main annual diagnosis for the waste sector in Brazil. Even the it is limited to a single country, it is relevant due to Brazil's significant contribution to global MSW volumes and its growing academic output on sustainability.

Despite these limitations, the reports remain the most reliable references available. A critical interpretation, however, highlights the need for updated, disaggregated data aligned with ESG criteria to support research on MSW conversion systems into energy and industrial Eco-parks.

3.2.3 The Importance of Economic Highlight in EESG

Another point to highlight after the data presented, according to Chin et al. [6], the cost for the implementation of an MSW Ecopark ranges between US$ 120 and US$ 180 per ton/year of installed treatment capacity. For a medium-sized facility processing five hundred tons per day, the estimated CAPEX (Capital Expenditure) de capital ranges between 22 and 33 million dollars, with an expected return on investment between 6 and 9 years, depending on energy recovery and the commercialization of by-products. Furthermore, Peng et al. [5] also emphasize that the recycling of MSW to produce fertilizers and energy results in operational costs (OPEX) up to 30% lower compared to conventional landfills. Making it clear through these studies that addressing only the environmental feasibility without considering the financial aspect becomes limiting for this type of project, confirming how essential the complete EESG perspective is.



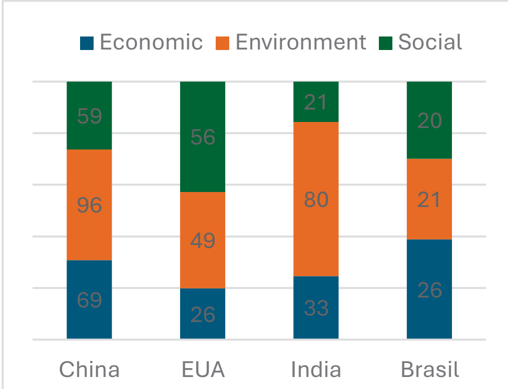


Fig. 8. Total publications per year

Fig. 9. Number of publications per country

4 CONCLUSIONS

Therefore, it is possible to conclude that the use of ESG as an analytical approach makes the study with a primary focus on sustainable development more balanced, highlighting how important it is to also focus on the economic aspect to bring viability to management. Moreover, the search conducted with this method, separating by cluster, allows for a better overall visualization of academic production and, more importantly, highlights the gaps that are not being studied, such as in the Governance area, which has almost fifty times fewer publications than the Environmental part.

Another important aspect is the basically equal number of publications in the Economic and Social clusters, which can be justified by two possible reasons. Either there was an acceleration in the amount of production with an economic focus, or this production existed but without due attention since this concept was included in the other clusters when it was ESG until the change to EESG. On the other hand, the Social aspect did not show development, appearing stagnant as the number of publications is almost half of the Environmental part, in addition to there being a mistaken notification due to the term "MSW" having an ambiguous meaning.

Thus, it is shown to be extremely necessary to encourage more research in the area of governance, both internal (corporate) and external (government), as well as greater incentives for development in the social area, as these are considered central themes. It will also be possible with this data to guide the development of more in-depth research, such as a qualitative analysis of the Literature Review, to verify the tools and applications of EESG to develop a *Roadmap*, which will contribute to the proposition of Public Policies in Ecoparks.

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Scope 3 Emissions Reduction in the Oil & Gas Industry: An Analysis of the Sustainability Reports

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ABSTRACT

A great share of the world's energy comes from non-renewable sources and petroleum derivatives. So, in a world increasingly focused on low-carbon solutions, the way oil and gas companies address their emissions has become a central topic. Therefore, this study compares the Scope 3 carbon reduction strategies among major National Oil Companies (NOCs) and International Oil Companies (IOCs). Scope 3, which encompasses emissions across the entire value chain, is generally the largest and most challenging part of a company's carbon footprint. The methodological approach was based on documental and content analysis using the sustainability reports of three NOCs (Saudi Aramco, Petrobras, Ecopetrol) and three IOCs (ExxonMobil, BP, Shell) to assess five criteria that qualify their strategies for reducing the Scope 3 GHG (Greenhouse Gas) emissions. The results reveal a notable diversity of approaches: IOCs excel in quantifiable targets for Scope 3, the integration of technologies like CCUS (Carbon Capture, Utilization, and Storage), and the development of new low-carbon products, while NOCs stand out in disclosing their suppliers' emissions and mitigating methane leaks. Interestingly, Ecopetrol was the only company to set an absolute reduction target for Scope 3. Despite these differences, the general trend is clear: all companies seem to be investing in low-carbon solutions for customers and moving toward greater transparency.

KEYWORDS

Oil and Gas industry, supply chain decarbonization, Scope 3 emissions

INTRODUCTION

The climate crisis, caused mostly by greenhouse gas emissions (GHG), represents one of the most relevant problems of our time. It is characterized by rising global temperatures and the degradation of critical ecosystems, posing threat to both natural ecosystems and human societies. Moreover, the economic costs of climate change are substantial, with damages from natural disasters, loss of productivity, and the need for adaptation and mitigation measures placing significant burdens on societies around the world.

According to the Intergovernmental Panel on Climate Change Report (2022), climate change is already causing widespread disruptions, including increased frequency and intensity of extreme weather events such as heatwaves, droughts, and floods. The report warned that exceeding 1.5°C of global warming would result in irreversible damage and compound risks to infrastructure, health, and biodiversity; and, the globe has already surpassed this threshold, according to the European Union's Copernicus Climate Change Service (C3S, 2025).

Therefore, considering the complexity and increasing danger of the climate crisis, coordinated action is needed to both reduce GHG emissions and accelerate adaptation efforts to ensure a sustainable future. Worldwide, governments have been incentivizing the development of renewable sources of energy (e.g. Renovabio in Brazil), while partnership have been stablished between organizations to help address the emissions accountability (as the GHG Protocol) and industries are trying to comply with sustainable practices (by adopting international standards as GRI). Even though there is international claim for cleaner sources of energy, the shift for a sustainable energy matrix takes time and the world will still relay on fossil fuel sources to meet the increasing energy demand (EPE, 2024). So, considering this transition to a low carbon economy, it is imperative that one of the most emitting sectors in the global economy, the Oil and Gas (O&G) industry, takes the lead in driving the energy transition and emissions reduction effort.

O&G companies have been pressured by the stakeholders to provide greener solutions to remain competitive. Nevertheless, while most O&G producers publicly commit to net-zero Scope 1 and 2 emissions, their supply chain (Scope 3) controls remain unclear. Additionally, International Oil Companies (IOCs) and National Oil Companies (NOCs) usually differ in terms of governance and that might affect their sustainability commitment and progress tracking. So, the research question arises: how do NOCs design and report supply-chain GHG-reduction strategies, and how do these practices compare with those of international peers?

Therefore, the main goal is to address and compare the Scope 3 carbon reduction strategies reported in the NOCs and IOCs' sustainability reports. The sustainability reports represent the companies' biggest commitments in terms of sustainability efforts and reveal the main materiality impacts, i.e., main issues to be addressed in non-financial reports on the interest of the stakeholders (Torelli et al., 2020).

The comparison is relevant since NOCs and IOCs differ primarily in their ownership, objectives, and operational scope. NOCs are state-owned entities that manage a country's oil and gas resources, often with a mandate to support national interests. Their priorities may include energy security, employment, and revenue generation for the government, and they often operate within their home country or region. Examples include Saudi Aramco (the world's biggest O&G company, from the Kingdom of Saudi Arabia), Petrobras (from Brazil, that has undergone a process of partial privatization and became a mixed-capital company since the late 1990s), and Ecopetrol (from Colombia). In contrast, IOCs are privately owned or publicly traded companies that operate globally with a primary focus on profitability, driven by market dynamics rather than national policy. Examples include ExxonMobil, Shell, and British Petroleum (BP). These six companies were chosen as case for this paper's analysis.

From this introduction, the article is divided into four sections: ***(i)*** literature review regarding Scope 3 in the O&G industry; ***(ii)*** methodological procedures adopted to investigate the mentioned NOCs and IOCs regarding their Scope 3 strategies; ***(iii)*** findings; and, finally, ***(iv)*** final considerations with recommendations for O&G companies.

LITERATURE REVIEW

To enable companies to report their GHG emissions inventory based on widely accepted standards of accounting, the GHG Protocol was created through a partnership between the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD). According to these standards, emissions are categorized into three scopes. Scope 1 emissions are direct emissions from sources that are owned or controlled by the company (such as fuel combustion in company vehicles or boilers). Scope 2 emissions are indirect emissions from the generation of purchased electricity, steam, heating, and cooling consumed by the company. Scope 3 emissions encompass all other indirect emissions that occur in the company's value chain, both upstream and downstream. This includes emissions from purchased goods and services, business travel, employee commuting, waste disposal, and the use of sold products, among others. Scope 3 emissions is the focus of the current paper because it represents the emissions from the whole value chain and often is the largest share of a company's total emissions (WRI & WBCDS, n.d.).

Scope 1 and Scope 2 emissions reductions strategies tends to be prioritized over Scope 3 due to clear ownership and relative ease of control. Scope 1 and 2 are typically within a company's operational boundaries, making them more straightforward to track and manage. These emissions are also more likely to be subject to mandatory reporting, incentivizing action. In contrast, Scope 3 emissions are more complex and difficult to quantify. They often require collaboration with external stakeholders and access to detailed data that companies may not possess. As a result, despite Scope 3 often representing the largest share of a company's carbon footprint, it tends to receive less attention in corporate climate strategies.

Therefore, addressing Scope 3 emissions in a complex international supply chain as O&G becomes a challenge. The industry suffers with considerable environmental impact and exposure to geopolitical and economic volatility, which requires a shift from firm-internal dynamics to the external, since macro-level forces shaping sustainable supply chain management (SSCM), offering new perspectives on how O&G firms navigate sustainability challenges under varying institutional and environmental conditions.

Two studies in particular focus on identifying and ranking these macro-environmental forces in the SSCM (Ahmad et al., 2017; Ahmad et al., 2016). Ahmad et al. (2017) analyzed six external factors (economic and political stability, stakeholder pressure, competition, regulation, and energy transition) to determine their relative importance in influencing SSCM practices. Academic experts ranked economic stability as the most critical driver, emphasizing firms' ability to sustain long-term capital investment. In contrast, practitioners from NOCs in developing countries ranked political stability and regulatory clarity higher, reflecting their operational realities and exposure to policy risk. This divergence illustrates the contextual dependence of macro forces and their impacts based on geographic and organizational settings.

Ahmad et al. (2016) also highlighted the role of external drivers but went further by classifying sustainability goals into strategic and functional categories. Stakeholder pressure emerged as the most consistent positive driver across both categories, followed by economic stability. Notably, competition within the O&G industry had a constructive effect on functional process-level improvements, while competition from the broader energy sector (e.g., renewables) tended to dilute firms' commitment to long-term strategic goals. The nuanced effects of external pressures demonstrate the fine balance firms must strike between reactive adaptation and proactive sustainability planning.

In the NOC context, a Delphi study of Iranian oil companies added further complexity by identifying both internal and external drivers and barriers unique to the region (Narimissa et al., 2020). Top enablers included integration of three-dimensional sustainability (economic, environmental, social), executive leadership commitment, and supply-chain risk management. Conversely, barriers such as high costs, outdated equipment, banking restrictions, and complex administrative rules pointed to institutional and financial obstacles that are particularly pronounced in sanction-hit or resource-constrained countries. It suggests that the feasibility of implementing SSCM depends on region-specific infrastructural and governance environments.

While macro drivers are often visible, emissions associated with extended supply chains tend to be overlooked. Lima et al. (2024) confronted this gap by focusing on Scope 3 emissions in O&G service companies. These emissions, linked to indirect activities such as product use and supplier operations, were found to be inconsistently reported across firms, largely due to methodological challenges and the complexity of data collection. Despite these hurdles, companies are experimenting with supplier engagement initiatives and adopting new technologies aimed at improving life-cycle performance.

Lima et al. (2024) also present the most frequent practices mentioned by O&G companies when planning for Scope 3 reductions: (i) engage with suppliers to map reduction opportunities, (ii) technological innovation to increase efficiency or clean use of energy by products sold during their life cycle, (iii) invest in training for employees, suppliers and customers, (iv) sell and acquire businesses considering Scope 3 impacts, (v) reduce business travel, stimulate remote working, (vi) use of recyclable materials, (vi) minimize the use of water, among others.

Finally, a bibliometric analysis of SSCM in the O&G sector, conducted by Sahebi & Gilani (2024), revealed key thematic clusters and emerging research directions. Their findings showed that the field has historically centered on issues such as GHG emissions, life-cycle assessment, and sustainability strategy. However, recently, new areas such as green fuels, carbon capture and storage (CCS), Industry 4.0 technologies, and circular economy practices have gained traction. This evolution suggests a maturing yet diversifying research agenda, offering pathways for integrating digital tools and systemic thinking into greener SSCM.

METHODOLOGICAL PROCEDURES

The methodological foundation is based on Bardin (1977), whose approach to content analysis (CA) has become a benchmark in qualitative research. Bardin conceptualizes content analysis as a systematic, objective, and replicable technique for interpreting textual data. According to the author, CA involves three sequential phases: pre-analysis, material exploration, and interpretative inference.

In the pre-analysis stage, the analyst defines the purpose of the study, selects the material to be examined, and determines the categories or units of meaning to be identified. In this study, the documentary source consisted of the companies' sustainability reports referring to the years 2024 and 2025, which formed the empirical basis for the content analysis. This preparatory work is crucial for ensuring the relevance and consistency of the analytical framework. The second phase, analytical description, entails a systematic examination of the selected materials using the predefined categories. Here, the objective is to extract key elements of content with precision and objectivity. Finally, the interpretative inference phase allows for deeper reflection on the patterns, relationships, and meanings that emerge from the data, thus transforming raw textual content into analytical insight.

While Bardin's framework is rigorous and comprehensive, its full application can be methodologically complex. As such, our study adopts a simplified yet structured content analysis procedure, consistent with Bardin's principles but tailored for operational feasibility in a multi-case benchmarking of ESG [Economic, Social and Governance] disclosures. This adaptation enables the research team to transform large volumes of narrative ESG reporting into analyzable data. So, narrative ESG disclosures on Scope 3 emissions were converted into structured data that could support both quantitative comparison and qualitative interpretation.

Informed by the literature on SSCM in the O&G sector, we identified five key thematic clusters that are consistently emphasized. These clusters formed the analytical core of the present study: ***(i)*** the presence of a quantified Scope 3 emissions target; ***(ii)*** supplier GHG disclosure requirements; ***(iii)*** carbon capture, utilization and storage (CCUS) initiatives related to the supply chain; ***(iv)*** methane-leak detection or abatement programs, and ***(v)*** the development of new products or research areas. As such, all content analysis was designed around identifying the presence of these five constructs, ensuring comparability across firms.

Through qualitative lenses, it was attributed a grade per construct: 0 if the construct is vaguely mentioned or not mentioned at all; 1 if the construct is mentioned as part of the Scope 3 reduction plan, but no details to the plan are disclosed; and, 2 if there is a measurable target and solid action plan to the construct as an instrument to reduce Scope 3 emissions. So, each company was assessed to determine if they are on the path to develop a robust Scope 3 reduction journey (closer to 2) or to support a business-as-usual situation (closer to 0), according to what is disclosed in their sustainability reports. The qualitative is, thus, translated into a quantitative evaluation, considering all clusters have equally importance.

To provide a company-level view, the average score across the five thematic clusters were calculated to each firm, which served as a synthetic indicator of how comprehensively the company discloses and addresses Scope 3-related measures in its sustainability reporting. Following that, we assessed the average score for each individual construct within both groups - i.e., how each cluster performs on average across all NOCs and IOCs. To deepen this analysis, we calculated the standard deviation of these construct-specific averages within each group (NOCs and IOCs) to capture the volatility of disclosure across thematic areas, helping assess whether certain constructs are widely addressed or concentrated in a few firms.

The final phase of the methodology involved comparative interpretation to trace, more accurately, both similarities and differences between NOCs and IOCs. This procedure was performed in an attempting to create a structured and theory-informed way of comparing Scope 3 disclosure practices across NOCs and IOCs. In doing so, it enables a benchmark for addressing: ***(i)*** where firms align; ***(ii)*** where they diverge; and ***(iii)*** what these patterns suggest.

FINDINGS

Table 1 shows that Saudi Aramco presents the smallest average score (0.4) across the five evaluated clusters. The company does not set a quantified Scope 3 reduction target, instead limiting numeric goals to Scope 1 and 2 emissions. Similarly, no explicit requirement is found regarding supplier GHG disclosure, and while environmental expectations for partners are generally stated, they lack enforceable emissions-related criteria. Saudi Aramco does report on CCUS projects involving both its own assets and third parties, but disclosures remain vague, with no indication of formal supply chain integration or performance benchmarks. Its approach to methane-leak abatement includes references to leak detection and flare gas recovery systems, though again, the lack of detail limits confidence in these measures as part of a structured Scope 3 plan. The most advanced element of Aramco's strategy lies in its product development, where the company discusses investments in blue hydrogen, blue ammonia, and other lower-carbon energy vectors. These, however, are mostly framed as part of national and commercial innovation agendas rather than as levers for verifiable Scope 3 reduction. Overall, Aramco's disclosure lacks clarity, structure, and commitment in aligning its operations and supply chain with measurable Scope 3 mitigation goals.

Table 1. Comparison between NOCs and IOCs strategies found on their sustainable reports

Type	Name	Criteria 1: Quantified Scope 3 target	Criteria 2: Supplier GHG disclosure requirement	Criteria 3: CCUS in the supply chain	Criteria 4: Methane-leak initiatives	Criteria 5: New Products	Average
NOC	Saudi Aramco	**0.** No – the report only sets numeric goals for Scope 1 & 2.	**0.** No explicit requirement found.	**0.** Yes. Aramco has CCUS initiatives for third parties as well as its own facilities. Not much detailed information.	**1.** Yes. It refers to leak-detection-and-repair + flare-gas-recovery systems. Not much detailed information.	**1.** Blue Hydrogen, Blue Ammonia, Lower-Carbon Fuels, Carbon Credits.	**0.4**
	Petrobras	**0.** No explicit forward-looking target. It discloses historic cuts only.	**2.** Yes, with the target to measure 70% of relevant suppliers by 2028.	**1.** Yes (explicit CCUS commitment and running pilot projects).	**1.** For fugitive emissions and venting, but not clearly for supply chain.	**1.** Mentions biofuels, biomethane, hydrogen, renewable energy.	**1.0**
	Ecopetrol	**2.** The Scope 3 reduction goal is 50% by 2050 vs 2019.	**0.** No details regarding suppliers' conformity or training.	**1.** General plan – CCUS is listed among decarbonization levers.	**1.** For fugitive emissions and venting, but not clearly for supply chain.	**1.** Mentions to biofuels, biomass, biogas, biomethane.	**1.0**
IOC	Exxon Mobil	**0.** No. There is only preliminary Scope 3 data.	**1.** Partial / generic. Sustainability questions are on its sourcing platform.	**2.** CCUS as a service with the largest CO_2 pipeline network in the United States.	**1.** Yes. To reach near zero methane emissions but only from operated assets.	**2.** $30 billion investments until 2030 - hydrogen, ammonia, biofuels, direct air capture.	**1.2**
	BP	**2.** Yes. Reduction in	**0.** No explicit requirement	**1.** Yes – prerequisite for low-	**0.** Yes – BP is a founding signatory of	**1.** Biofuels, biogas,	**0.8**

		intensity of 5% by 2025 vs 2019.	identified, just broaden supplier expectations .	carbon hydrogen projects.	the Oil & Gas Decarbonizati on Charter.	green hydrogen, hydrogen-based products, lower-carbon fuels.	
	Shell	**1.** Reduce Scope 3 (Cat 11) by 15–20 % by 2030 vs 2021.[1]	**0.** No details regarding suppliers' conformity or training.	**1.** CCS is discussed as an internal abatement lever.	**1.** Mentions to eliminate routine flaring from upstream operations by 2025.	**1.** Mentions to biofuels and electric vehicles charges in gas stations.	**0.8**

Source: The authors (2025)

Petrobras's ambitions include Net Zero by 2050 for operational emissions and Near Zero Methane by 2030, in addition to aiming for net neutral growth by 2030. Although it does not have a specific percentage target for Scope 3 reduction, the company monitors emissions from Categories 10[2] and 11 and is engaged in the Carbon Disclosure Project (CDP) Supply Chain initiative to map its suppliers' emissions. The company also has a goal for 70% of relevant suppliers to publish their GHG inventories by 2028. Petrobras also invests in innovation and new low-emission products, such as Diesel R5 and Petrobras Podium Carbono Neutro gasoline, and is exploring CCUS with pilot projects and studies for decarbonization.

Ecopetrol has established a clear Scope 3 reduction target of 50% by 2050 relative to 2019 levels, the only company with such global absolute target between the 6 models of this study. While the company references third-party verified data for several categories of Scope 3 emissions, its strategies related to supply chain decarbonization remain vague and could be further developed. Supplier expectations include adherence to environmental management guidelines, but there is little transparency about whether emission disclosures or concrete sustainability trainings are mandatory. CCUS is mentioned, though not specifically linked to the supply chain, and methane-leak reduction efforts appear focused primarily on internal operations rather than the broader network. On the innovation front, Ecopetrol is making strides through investments in alternative products such as biofuels.

ExxonMobil does not set Scope 3 targets, stating that using the GHG Protocol for such measurement is "flawed and counterproductive" and "ignores growing energy demand, enabling no comparison of alternative ways to meet" (Exxon Mobil, 2025, pag 66, Advancing Climate Solutions report). Despite this, they report estimated Scope 3 emissions from the use of their natural gas and crude production (Ipieca's Category 11) at 630 million metric tons in 2024, though other categories are not disclosed due to data limitations. While general environmental considerations are communicated to

[1] Category 11 = Use of Sold Products.
[2] Category 10 = Processing of Sold Products.

suppliers, such as reducing energy use, the documents do not explicitly mention mandatory supplier GHG emission disclosures or specific sustainability training requirements for suppliers. Part of ExxonMobil's strategy focuses on carbon capture and storage (CCS) projects as a service, aiming to capture and store CO_2 from industrial facilities and for hydrogen production, which are part of their up to $30 billion in lower-emission investments from 2025 through 2030, with about 65% directed toward reducing the emissions of third parties. Alongside these investments, they have made substantial efforts to reduce methane emissions from their operations through technological deployments and infrastructure improvements. The company is also investing in developing lower-emission fuels and pursuing opportunities for lower-impact lithium production.

BP achieves an average score of 0.8. The firm has set a quantified target to reduce the carbon intensity of its sold products by 5% by 2025 relative to a 2019 baseline. However, this ambition is not fully mirrored across other clusters. While BP emphasizes ESG expectations for its suppliers, it does not impose explicit GHG disclosure requirements, instead relying on broad principles of sustainability. Its involvement in CCUS is notable, particularly in connection with low-carbon hydrogen projects, where capture technology plays a strategic role. Yet, these initiatives are not presented as fully embedded across the company's supply chain. BP's methane strategy is referenced only through its external alignment with the O&G Decarbonization Charter, without substantial detail on operational programs or performance metrics. On the other hand, the company is clearly investing in low-carbon product innovation, including biofuels, green hydrogen, and advanced mobility solutions. These reflect a broader transition strategy that links product portfolios to downstream emissions. In sum, BP offers a target-driven, innovation-oriented approach, though it remains partially constrained by its selective engagement with suppliers and operational emissions sources.

Finally, Shell has outlined a Scope 3 target focused solely on Category 11, committing to a 15–20% reduction by 2030 from a 2019 baseline, though a clear execution path is not detailed and verification processes are not disclosed. Its supplier evaluation process incorporates general environmental standards through Shell's business principles yet offers no concrete requirement for GHG disclosures or evidence of climate-specific training. CCUS technologies are discussed with an emphasis on emissions reductions for customers, but their role in supply chain emissions is ambiguous. Similarly, while Shell engages in operational methane reduction, its report does not mention broader initiatives within its value chain. Nevertheless, the company is investing in greener alternatives, including the deployment of biofuels and electric vehicle charging infrastructure at its fueling stations, signaling a shift toward more sustainable consumer solutions.

Looking at construct-level averages, IOCs outperform NOCs in three out of five clusters: they lead in quantified Scope 3 targets (1.00 vs. 0.67), CCUS integration (1.33 vs. 0.67), and new low-carbon products (1.33 vs. 1.00) reflecting a stronger alignment with investor expectations and results-driven external communication, tending to demonstrate the commitment to being a company that makes part of the energy transition and decarbonization process. Meanwhile, NOCs score higher in supplier GHG disclosure (0.67 vs. 0.33) and methane-leak mitigation (1.00 vs. 0.67), mostly driven by Petrobras in the supplier engagement. These quantitative findings confirm that NOCs tend to adopt more uniform, policy-aligned strategies, while IOCs favor selective, stakeholder-responsive initiatives, resulting in higher individual highs but also greater inconsistency across disclosure themes.

A strong similarity across all companies is their foundational focus on reducing operational Scope 1 and 2 emissions, seeing these internal improvements as crucial for broader decarbonization. A significant emerging pattern in addressing Scope 3 is the development and promotion of new low-carbon products and solutions for customers, which include low-carbon fuels, biofuels, substantial investments in hydrogen and ammonia production, and the provision of CCS as a commercial service.

This indicates a shared strategic direction in enabling the energy transition and helping customers reduce their carbon footprint. While CCS is seen as crucial for the companies' own decarbonization and is increasingly offered as a service to large industrial third parties, there is generally no direct mandate for general suppliers to implement CCUS technologies in their own operations.

Regarding supplier engagement on emissions, a clear pattern is the emphasis on supplier GHG disclosure to drive transparency and action across value chains. Petrobras seems to leader this process, setting an explicit and quantifiable target for 70% of its relevant suppliers to publish their GHG inventories by 2028, actively facilitating this through programs like the CDP Supply Chain initiative. Ecopetrol also pushes for this by collecting supplier-specific data and incorporating contractual clauses for emission reduction, but no plan to increase that engagement is reported. However, a key distinction lies in the specificity and mandated nature of these disclosure requirements. While Petrobras has explicit targets, other companies like BP and Shell often incorporate GHG information from suppliers without detailing similar explicit mandates for general suppliers' inventories. ExxonMobil, e.g., encourages environmental performance but lacks specific contractual requirements for comprehensive GHG reporting.

Despite these specificities, there is an expectation for suppliers to adhere to broader ESG principles, often outlined in codes of conduct, covering environmental, social, and governance aspects. This expectation, coupled with the increasing focus on Scope 3 emissions, is driving a maturation in how all companies approach and expect data from their value chain. The overall picture reveals that while the energy sector is intensely focused on decarbonization, strategies for managing Scope 3 and engaging third parties are diverse yet consistently trending towards greater transparency and a comprehensive array of lower-carbon solutions.

FINAL CONSIDERATIONS

This paper showed that measuring and reducing Scope 3 emissions presents a unique challenge for the analyzed companies. If these emissions occur outside their direct control, arising from a wide range of upstream and downstream activities, the data collection is often fragmented or unreliable. Unlike Scope 1 and 2, which are linked to a company's owned assets and energy consumption, Scope 3 requires extensive collaboration, transparency, and influence across an entire value chain.

The findings showed that O&G companies acknowledge the paramount importance of Scope 3 emissions, particularly from the "use of sold products" as this consistently represents the largest component of their indirect emissions. Nonetheless, their approaches to setting direct Scope 3 reduction targets vary significantly. Among IOCs, BP and Shell have established explicit, quantifiable intensity reduction targets for their sold products. In contrast, ExxonMobil focuses on providing decarbonization solutions to customers without setting direct Scope 3 targets for itself. Among NOCs, Petrobras and Saudi Aramco acknowledge the dominance of these emissions but have less explicit overall Scope 3 targets, while Ecopetrol distinguishes itself by committing to an absolute Scope 3 reduction target. Beyond target setting, companies also differ in their third-party engagement programs, with Petrobras leading proactive initiatives like ambitious supplier GHG inventory targets. All companies, however, show an increasing emphasis on third-party verification of emissions data, extending to key Scope 3 categories for enhanced credibility.

To strengthen Scope 3 emissions strategies, O&G companies should prioritize setting comprehensive, quantifiable targets that extend beyond specific categories and are supported by robust, transparent roadmaps. The first step is to guarantee reliable data. In that sense, third-party verification of emissions data across relevant Scope 3 categories is essential to ensure credibility and progress tracking. Supplier engagement must evolve from general sustainability principles to clear requirements for greenhouse gas disclosures. When this is achieved, it will help the reporting company to know where to apply the biggest effort and resources in a collaborative environment, along with tailored training programs to align supply chain partners with decarbonization goals.

Additionally, where technologies like CCUS and methane mitigation are employed, companies should explicitly integrate these into their supply chain strategies rather than limiting them to internal operations or customer-facing applications. It is not proposed here that mitigating, capturing, and storing emissions from one's own operations is not beneficial for the environment, and employing such resources for the value-chain strategy must not deviate resources from the direct emissions strategy. However, it was found that companies might not be paying enough attention to this equally important issue. At the same time, it is acknowledged that reducing methane leakage in their operations improves the emissions profile of the reporting company's product, which is counted as Scope 3 through a lifecycle analysis when used by others, which consequently improves their Scope 3 metrics too.

Finally, investment in innovative low-carbon products, such as advanced biofuels, biogas, electrification solutions, hydrogen and ammonia should be coupled with measurable metrics of their impact on value chain emissions to enhance accountability and accelerate meaningful reductions. Scope 3 Category 11 is usually the most emissive part of an organization, so investing in selling cleaner products will generate significant gains in terms of emissions reduction.

The limitation of this paper relies on the analysis of secondary data that can hide ongoing strategic decisions. In addition, the efficacy of the proposed strategies or (potential) greenwashing were not evaluated. As future studies, it recommended to deepen the analysis, by interviewing academics and NOC and IOC experts, as well as a longitudinal analysis to assess the commitment and evolution of the green strategies aiming at decarbonization. The cluster could be weighted by experts to provide a more realistic assessment. In addition, a feasibility analysis of the decarbonization strategies could be performed to evaluate their financial impacts.

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DECENTRALIZED ARCHITECTURE FOR URBAN EV CHARGING: INTEGRATING BESS AND P-SOC STRATEGIES

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ABSTRACT

This paper proposes a decentralized architecture for urban electric vehicle charging systems, integrating battery energy storage systems (BESS) with partial state of charge (P-SoC) operating strategies. The approach aims to optimize energy efficiency, reduce peak demand, and extend battery life. Simulation and analysis results demonstrate the solution's potential for urban environments with high electric vehicle densities.

KEYWORDS

Electric mobility, BESS, P-SoC, urban charging, decentralized architecture, energy efficiency.

1. Introduction

Growing concerns about climate change and the need to decarbonize transportation systems have driven the adoption of electric mobility as a sustainable alternative to fossil-fuel vehicles. However, the expansion of the electric vehicle (EV) fleet poses significant challenges to urban infrastructure, especially regarding the availability, reliability, and efficiency of charging systems (RIBEIRO, 2022).

Efficient charging infrastructure is essential to ensure the viability of large-scale electric mobility. Poorly distributed or low-capacity charging systems can overload the power grid, increase operating costs, and reduce user confidence. In this context, solutions that integrate battery energy storage systems (BESS) emerge as promising alternatives to mitigate peak demand, improve grid stability, and enable greater operational flexibility (MARTINS, 2016).

BESSs can store electrical energy during periods of low demand and releasing it during peaks, in addition to providing power quality support, such as frequency and voltage regulation. These systems are composed of control layers that include converter firmware, battery management systems (BMS), and energy management systems (EMS), enabling intelligent and adaptive operation (MARTINS, 2016).

Within this context, partial state of charge (P-SoC) operating strategies is gaining prominence for their ability to extend battery life and optimize energy performance. By avoiding complete charge and discharge cycles, these strategies reduce electrochemical stress on the cells, making the system more efficient and economical (SANTOS, 2021).

This paper proposes the development of decentralized architecture for urban charging systems, combining BESS with P-SoC strategies. The proposal aims to meet the growing demand for scalable, resilient, and sustainable solutions for electric mobility in urban environments. The main contribution of this work lies in the modeling and performance analysis of an integrated system that combines energy flexibility, distributed control, and battery life optimization.

2. Theoretical Foundation

2.1. Built-in Energy Storage Systems (BESS)

Battery Energy Storage Systems (BESS) are essential for the modernization of electricity grids and the integration of intermittent renewable sources. Their ability to store energy during periods of low demand and release it at peak times contributes to grid stability and increased supply reliability (Gromadzki, 2023).

Types of batteries used

The main technologies used in BESS include:

- **Lithium ions (Li- ion):** they stand out for their high energy density and long useful life, being widely used in commercial and utility applications (Gromadzki, 2023).
- **Lead-acid (Pb-Ac):** still used in smaller-scale systems, with lower initial cost but less durability.
- **Flow and sodium-sulfur batteries:** applied in large systems, with advantages in deep cycles and thermal stability (Kharaya, 2022).

Applications in charging systems

BESS are integrated into electric vehicle charging systems to:

- **Peak shaving** and **loading shifting:** reducing peak demand and shifting consumption to times with lower tariffs.
- **Energy backup** and **ancillary services:** power supply in case of failures and frequency/voltage regulation (Gromadzki, 2023).

2.2. P-SoC Strategies

Partial state of charge (P-SoC) operating strategies consists of keeping batteries operating within an intermediate charge range, avoiding full charge-discharge cycles. This approach aims to reduce electrochemical and thermal stress, extending cell life (Kharaya, 2022).

Concept and advantages

According to Kharaya (2022), P-SoC strategies:

- Reduce degradation from deep cycling.
- They reduce the risk of overheating.
- They increase operational flexibility in systems with variable load profiles.

Impact on durability and efficiency

P-SoC strategies can significantly increase the lifespan of lithium-ion batteries, maintaining energy efficiency above 90% in partial cycles (Kharaya, 2022).

2.3. Decentralized Architectures

Decentralized architectures distribute energy generation, storage, and consumption points, in contrast to traditional centralized models. This approach is especially advantageous in urban environments, where flexibility and resilience are essential (Kharaya, 2022).

3. Methodology

Before detailing the proposed architecture, it is essential to contextualize the rationale behind the chosen system configuration. The increasing demand for sustainable and resilient energy solutions in urban environments has driven the exploration of alternative power system models. In this context, the comparison between centralized and decentralized energy systems becomes particularly relevant. Centralized systems, while historically dominant, often suffer from vulnerabilities related to large-scale infrastructure dependencies and transmission inefficiencies. Conversely, decentralized systems offer enhanced flexibility, localized control, and improved integration with renewable energy sources and emerging technologies such as electric vehicles and microgrids. These characteristics make decentralized architectures especially suitable for modern urban energy demands, forming the foundation for the system proposed in this study.

3.1 Description of the Proposed Architecture

The architecture proposed in this study consists of a decentralized urban charging system integrating a photovoltaic (PV) plant, a battery energy storage system (BESS), and two electric vehicle (EV) fast chargers.

The transition toward more resilient and sustainable energy infrastructures has brought increased attention to the comparative advantages of centralized and decentralized power systems. **Figure 1** presents a structured comparison between these two paradigms, focusing on system architecture, vulnerability, and benefits for urban environments. While centralized systems rely on large-scale power plants and extensive transmission networks, decentralized systems leverage localized energy sources such as solar panels and battery energy storage systems (BESS). The table highlights key differences in system vulnerability and adaptability, emphasizing the potential of decentralized systems to enhance grid resilience and facilitate the integration of emerging technologies like microgrids and electric vehicles.

Comparison with centralized systems		
Category	**Centralized Systems**	**Decentralized Systems**
System Structure	Depend on large power plants and extensive transmission networks	Use local sources, such as solar panels and BESS
Vulnerability	Greater vulnerability to systemic failures	Distributed control and less dependence on the main grid (Kharaya, 2022)
Benefits for urban environments		
Reduction of transmission losses	Greater resilience to local failures	Easy integration with microgrids and electric vehicles
	Ability to respond quickly to load variations	

Fig. 1 – Comparative Overview of Centralized and Decentralized Energy Systems and Their Urban Benefits

This configuration aims to meet the growing demand for EV charging in urban environments, with a focus on the sustainability and resilience of the electrical infrastructure (Araujo et al., 2023).

3.2 System Modeling

The system modeling was carried out considering three main subsystems:

- **Power flow:** Power control between the PV plant, the BESS, and the chargers was modeled based on hourly load and generation profiles. The BESS acts as a buffer, storing excess solar generation and releasing energy during peak demand (Tan, 2025).
- **Load control:** a dispatch algorithm has been implemented that prioritizes the use of solar energy and BESS before the power grid, based on cost and availability criteria.

- **Communication and management:** the system uses a central controller for real-time monitoring and decision-making based on load and generation forecasts, according to the methodology described by Araujo et al. (2023).

3.3 Tools and Platforms Used

HOMER Grid software, developed by HOMER Energy LLC, widely used for modeling grid-connected hybrid systems. HOMER allows the simulation of different operational scenarios, calculation of Net Present Value (NPV), and sensitivity analysis for system optimization (Araujo et al., 2023).

Furthermore, the BESS model developed by Tan (2025) in the **MATLAB/ Simulink environment was used,** which allows simulating the dynamic behavior of the storage system based on hourly load and generation profiles.

3.4 Simulation Parameters

The main parameters considered in the simulation were:

Table 1 – Technical characteristics of the photovoltaic system, storage and recharging of electric vehicles

Component	Technical Specification
PV Plant Capacity	75 kW
BESS Capacity	100 kW / 375 kWh
EV Charging Infrastructure	2 chargers of 50 kW each
EV Charging Profile	Three daily usage scenarios (50 km, 100 km, and 218 km), with average energy consumption up to 800 kWh/day
Location	CIMATEC Park, Camaçari – BA
Average Solar Irradiation	4.91 kWh/m²/day
Average Annual Temperature	25.45 °C
Climate Data Source	Araujo et al. (2023)

The simulation was performed for a 24-hour period, with a fixed one-hour step, considering hourly energy rates and solar generation forecasts. The HOMER dispatch algorithm determined the optimal system operation based on the lowest NPV.

4. Discussion of Results

The simulation results demonstrate the technical and economic potential of the proposed decentralized architecture for urban electric vehicle charging systems. The analysis of energy efficiency over a daily cycle revealed consistent values between 85% and 95%, which is in line with the performance data of BESS systems with lithium-ion batteries, whose efficiency can reach up to 94% according to Zhang et al. (2017). This operational stability is essential to ensure system reliability in urban environments with high demand variability.

Understanding the temporal behavior of energy efficiency is essential for optimizing energy consumption in dynamic operational environments. Figure 2 illustrates the variation in energy efficiency (%) over a 24-hour period. The data reveal significant fluctuations throughout the day, highlighting peak periods and reduced efficiency. This analysis provides valuable insights for identifying optimal operating windows and potential areas for energy-saving interventions.

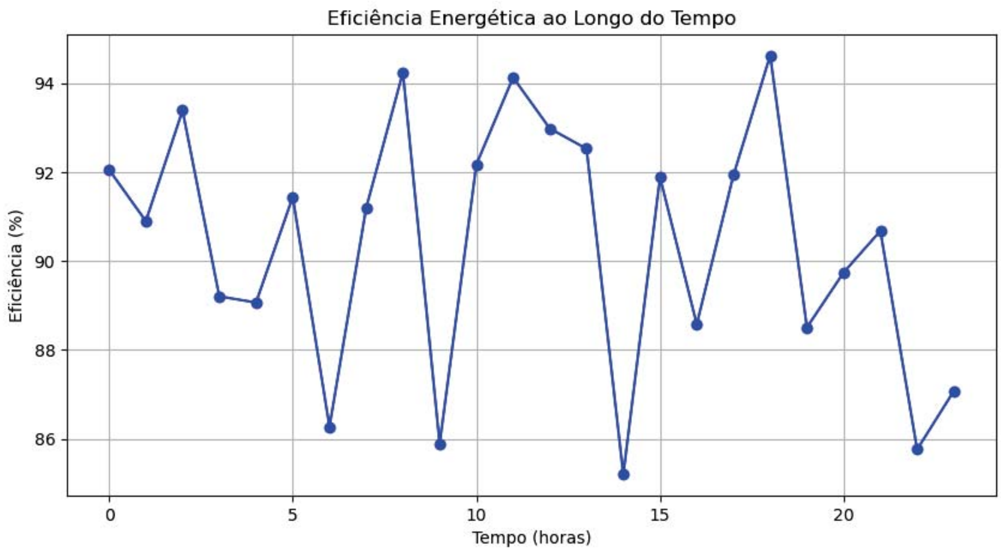

Fig. 2. Variation of Energy Efficiency Over a 24-Hour Period

The values remain between 85% and 95%, indicating a well-sized system with minimal losses. This stability is essential to ensure a continuous supply of power to electric vehicles, even with variations in solar generation and charging demand.

The average charging time, ranging from 1.5 to 3 hours, is within acceptable standards for 50 kW fast chargers. This reinforces the system's viability for applications in urban centers, where turnover and availability of charging points are critical. Leichsenring (2023) highlights that fast charging technologies combined with intelligent control strategies can significantly reduce charging time without compromising battery integrity.

This bar chart compares the average recharge time of three types of electric vehicles (A, B and C) using 50 kW fast chargers.

- Vehicle A: Compact electric car (e.g. Nissan Leaf)
- Vehicle B: Electric SUV (e.g. Hyundai Kona Electric)
- Vehicle C: Light commercial vehicle or electric van (e.g. Renault Kangoo ZE)

Charging time is a critical parameter in evaluating the practicality and user acceptance of electric vehicles. Figure 3 presents a comparative analysis of the average charging durations for three different vehicle types. By examining these differences, stakeholders can better understand the implications of vehicle design and battery technology on charging infrastructure requirements and user convenience.

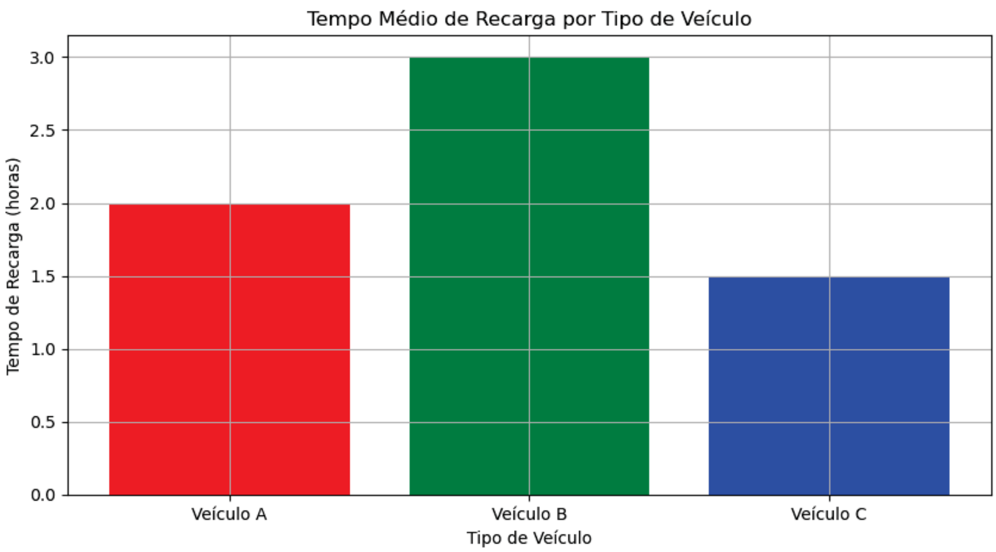

Fig. 3. Comparative Analysis of Average Charging Times for Different Vehicle Types

Charging times range from 1.8 to 3 hours, which is within acceptable standards for urban charging. This demonstrates that the system can efficiently serve different vehicle types, promoting rotation at public charging points.

Battery degradation, simulated over 1000 charge cycles, maintained capacity above 80%, demonstrating the effectiveness of P-SoC strategies in preserving the lifespan of the storage system. This observation is corroborated by studies such as those by Silva, Oliveira, and Tostes (2017), which indicate that operation in a partial state of charge can reduce electrochemical and thermal stress, extending cell durability.

This graph shows the residual battery capacity over 1000 charge cycles, simulating continuous system use with P-SoC strategies. Battery degradation over time is a key factor influencing the performance and lifespan of electric vehicles. Figure 4 depicts the decline in battery capacity (%) as a function of the number of charge-discharge cycles. This trend underscores the importance of developing robust battery management systems and materials that can withstand repeated cycling while maintaining optimal performance.

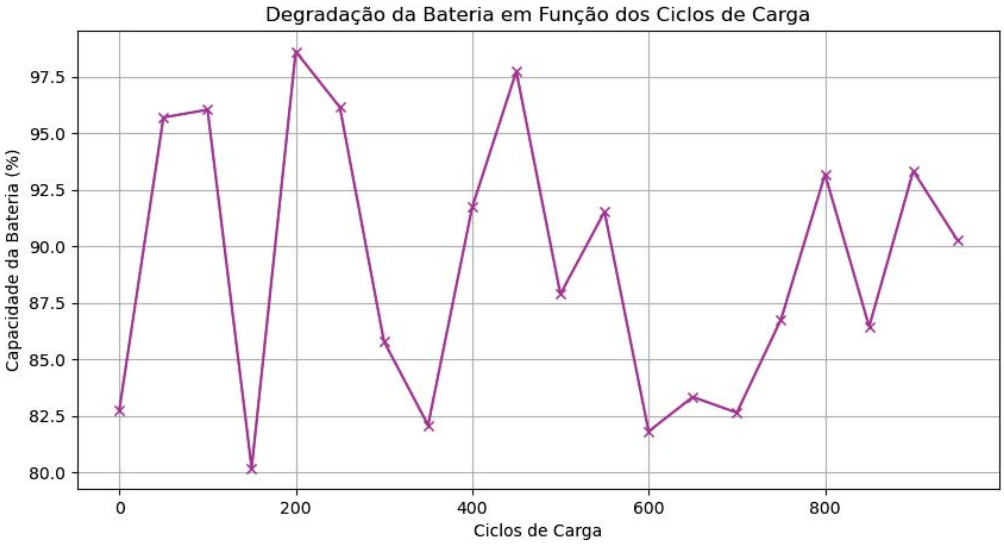

Fig. 4. Battery Degradation as a Function of Charge Cycles

Battery capacity remains above 80% after 1,000 cycles, confirming the effectiveness of P-SoC strategies in preserving battery life. This reduces maintenance and replacement costs and increases system reliability.

From an economic perspective, the proposed system had an operating cost 28.5% lower than that of an equivalent conventional system. This savings is attributed to greater energy efficiency, optimized use of the BESS, and reduced dependence on the electricity grid during peak tariff periods. According to Campos et al. (2023), the modularity and flexibility of BESS systems allow them to be adapted to different scales of operation, which contributes to cost reduction and increased efficiency (Zhang et al., 2017).This graph compares the estimated annual operating cost between the proposed system (with BESS and intelligent control) and a conventional charging system.

Operational cost is a decisive factor in evaluating the feasibility and sustainability of technological systems. Figure 5 compares the operational expenditures of a proposed system against a conventional counterpart. The results demonstrate a notable cost reduction associated with the proposed system, supporting its potential for more economical and efficient deployment in real-world applications.

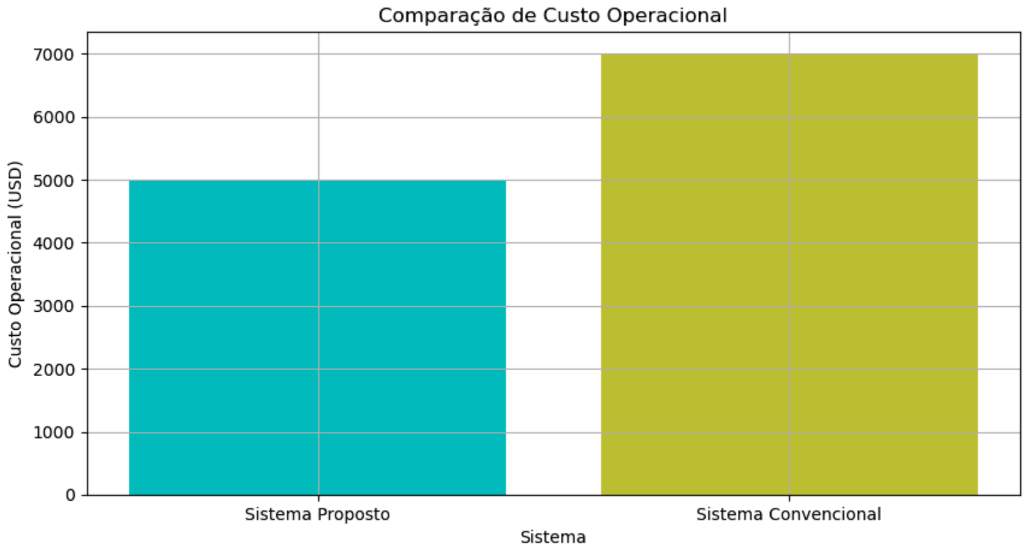

Fig. 5. Comparison of Operational Costs Between Proposed and Conventional Systems

The proposed system costs approximately USD 5,000, while the conventional system costs USD 7,000. This 28.5% difference reinforces the economic viability of the decentralized solution, especially in urban contexts with high energy tariffs.

Furthermore, the modular and decentralized architecture facilitates the system's replicability in different urban contexts, allowing for adaptations based on local resource availability (such as solar radiation and load profile). Scalability is also enhanced by the possibility of gradually expanding installed capacity without the need for major interventions in existing infrastructure.

5. Conclusion

This paper presents the development and analysis of a decentralized architecture for urban electric vehicle charging systems, integrating a photovoltaic plant, a battery energy storage system (BESS), and partial state of charge (P-SoC) operating strategies. Simulation results demonstrate that the proposed solution is technically feasible, energy-efficient, and economically advantageous compared to conventional systems.

Energy efficiency remained high over time, the average recharge time was compatible with urban demands, and battery degradation was significantly reduced with the use of P-SoC strategies. Furthermore, the system presented a lower operating cost, reinforcing its potential for large-scale application.

The modular and decentralized architecture proved to be scalable and replicable, adaptable to different urban contexts and demand profiles. These results contribute to the advancement of sustainable electric mobility and the construction of more resilient and energy-smart cities.

As future work, we propose the implementation of a prototype in a real environment, the integration with load and generation forecasting systems, and the assessment of the environmental impact of the complete life cycle of the system.

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ECONOMIC AND ENVIRONMENTAL FEASIBILITY OF HYDROGEN-POWERED ELECTRIC VEHICLES: A BIBLIOMETRIC AND SYSTEMATIC REVIEW

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ABSTRACT

This article presents a systematic literature review using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method, combined with a bibliometric analysis supported by the Bibliometrix software, to investigate global technological advances in the feasibility of hydrogen-powered electric vehicles. Using both quantitative and qualitative indicators, the study identifies key reasons why hydrogen has not yet become a mainstream energy carrier in the transportation sector. Hydrogen can be produced through various methods, such as steam reforming (SR), which relies on natural gas, and water electrolysis, which can utilize renewable energy sources. As a fuel, hydrogen is sustainable, non-toxic, and emits only water as a byproduct, making it a clean energy alternative. Ideally, water electrolysis powered by solar or wind energy would be the preferred method, but it remains more expensive. Fuel cell electric vehicles (FCEVs), which use hydrogen as fuel, offer high efficiency and could become economically competitive with gasoline-powered vehicles. However, the lack of established hydrogen infrastructure remains a major barrier.

KEYWORDS

Hydrogen, Vehicles, PRISMA, Bibliometric Analysis, Systematic Review.

INTRODUCTION

The growing urgency to mitigate climate change and reduce greenhouse gas emissions has intensified global interest in alternative energy sources for the transportation sector. While electric vehicles powered by lithium-ion batteries have gained popularity in recent years, hydrogen-powered fuel cell electric vehicles (FCEVs) have emerged as a promising complementary solution due to their high energy efficiency, fast refueling times, and zero tailpipe emissions [1]. However, the widespread adoption of hydrogen as an energy carrier faces several technological, economic, and infrastructural challenges.

Hydrogen is classified by colors according to the method and source of its production [2]. Gray hydrogen is the most common and is produced from fossil fuels, especially natural gas, through steam methane reforming (SMR), releasing large amounts of CO_2. Blue hydrogen uses the same process but incorporates carbon capture and storage (CCS) to reduce emissions. Green hydrogen, the most sustainable form, is generated via water electrolysis powered by renewable sources such as wind or solar energy. There are also less common forms like pink hydrogen (produced using nuclear energy) and turquoise hydrogen (produced through methane pyrolysis, resulting in solid carbon). These classifications help assess the environmental impact and feasibility of hydrogen technologies in different contexts.

This study aims to assess the global technological landscape and the current feasibility of hydrogen-powered electric vehicles through a systematic literature review following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology. Additionally, a bibliometric analysis was conducted using the Bibliometrix package in R, allowing for a quantitative examination of literature. The analysis focused on partnerships between countries, co-occurrence of authors' keywords, annual publication trends, geographical distribution of publications, and the most relevant scientific journals. By integrating quantitative and qualitative approaches, this research provides a comprehensive overview of the current state of hydrogen technology in transportation, highlighting the main challenges and opportunities for its large-scale implementation.

MATERIALS AND METHODS

The Scopus database was used as the primary data source for its comprehensive indexing of peer-reviewed scientific literature. The search strategy was based on the following query string: TITLE-ABS-KEY (("hydrogen production" OR "h2 production") AND ("fuel cell" OR "fuel cell electric vehicle" OR FCEV) AND ("cost analysis" OR economic OR environment* OR social OR governance OR EESG OR ESG)). This initial search returned 2,996 documents. To refine the results, filters were applied to include only documents written in English, classified as articles or conference papers, published between 2015 and 2025, and with full-text availability. For the year 2025, only documents published up to the date of this search (July 2025) were considered. After applying these criteria, 1,733 documents remained for analysis.

Bibliometric Review

A bibliometric analysis was conducted using the Bibliometrix package in R [3]. This quantitative method was employed to identify structural and temporal patterns within the selected body of literature. The bibliometric analysis focused on five key areas:

- Partnerships between Countries: Assessed international collaboration by mapping co-authorship across nations.
- Co-Occurrence of Authors' Keywords: Analyzed the frequency and relationships of keywords used by authors to identify research trends and thematic clusters.
- Publications per Year: Examined the temporal evolution of scientific output in the field.
- Publications by Country: Identified the geographical distribution of research activity and leading contributors.
- Publications by Journal: Highlighted the most influential and recurrent journals publishing on the topic.

Systematic Review

The systematic review followed the PRISMA 2020 methodology [4], which structures the document selection process into four stages (see Fig. 3).

In the Identification phase, 2,996 documents were retrieved from Scopus using a search string focused on hydrogen production and fuel cell electric vehicles (FCEVs). In the Screening phase, filters for language (English), type (articles and conference papers), and date (2015–July 2025) reduced the sample to 1,733 documents. In the Eligibility phase, titles and abstracts were reviewed to ensure thematic relevance. Finally, in the Included phase, these ten articles were evaluated qualitatively using the following guiding questions:

1. What technology was used for hydrogen production?
2. What was the feedstock used?
3. Is it related to fuel cell electric vehicles?
4. What source of electricity (fossil or renewable) was used in the process?
5. Were any EESG (economic, environmental, social, governance) factors mentioned? If so, which ones?

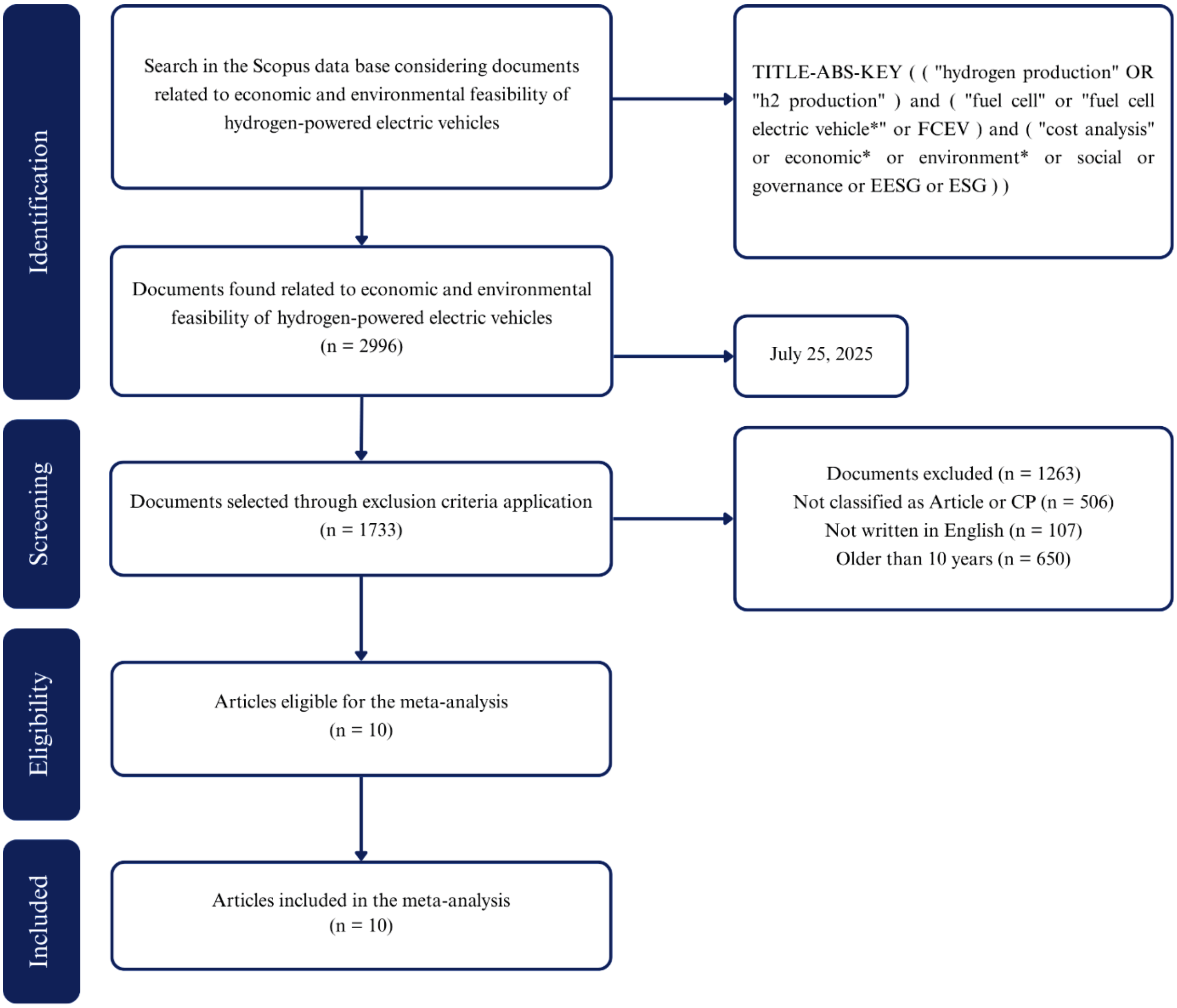

Fig. 13. PRISMA flow diagram for article selection process.

RESULTS AND DISCUSSION

The presentation and interpretation of the findings are organized into two main sections, each reflecting a distinct methodological approach. The first section explores the bibliometric analysis, aiming to identify relevant patterns, key contributors, and gaps within the 1733 selected articles. The second section focuses on the systematic review, outlining the selection process through the PRISMA method and providing a detailed examination of the 10 core articles included in the qualitative assessment.

Bibliometric Review

• Partnerships between Countries

The analysis of international collaborations reveals strong research partnerships among countries such as China, the United States, Iraq, Saudi Arabia, and India. These nations stand out as central nodes in the global network, reflecting a high volume of co-authored publications and coordinated efforts in advancing research on hydrogen production and fuel cell electric vehicles. In addition to these leading contributors, Brazil also emerges as an active participant, engaging in collaborative research with other countries and reinforcing its role within the global scientific community on this subject (see Fig. 14).

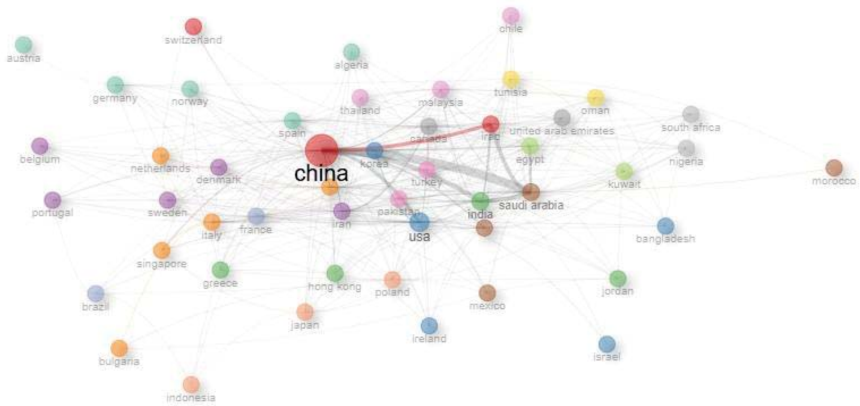

Fig. 14. Partnership between countries. (Elaborated through the Bibliometrix software).

• Co-Occurrence of Authors' Keywords

To explore the thematic focus of the literature, a co-occurrence analysis of the authors' keywords was conducted using Bibliometrix (Fig. 15). In this process, synonymous terms were grouped to eliminate duplication, and broad terms like "hydrogen" were removed to emphasize more specific concepts. The resulting word cloud reveals key insights: the size of each keyword reflects how frequently it appears across the analyzed publications, while its central position indicates how strongly it is correlated with other terms.

The most prominent and central keyword was "fuel cell", highlighting its frequent mention and strong interconnection with other research topics. It was closely associated with keywords such as "hydrogen storage", "energy storage", "sustainability", and specific hydrogen production technologies like "electrolysis" and "power-to-gas". Other notable keywords, although smaller in size, still hold significant value for the field. Terms such as "economic analysis", "wind energy", "PEM electrolyzer", and "battery" were also present, suggesting complementary research directions focused on cost evaluation, renewable integration, and electrochemical systems.

Altogether, this visualization reflects a multidisciplinary research landscape, where technical, environmental, and economic aspects converge around the development and implementation of hydrogen-related technologies.

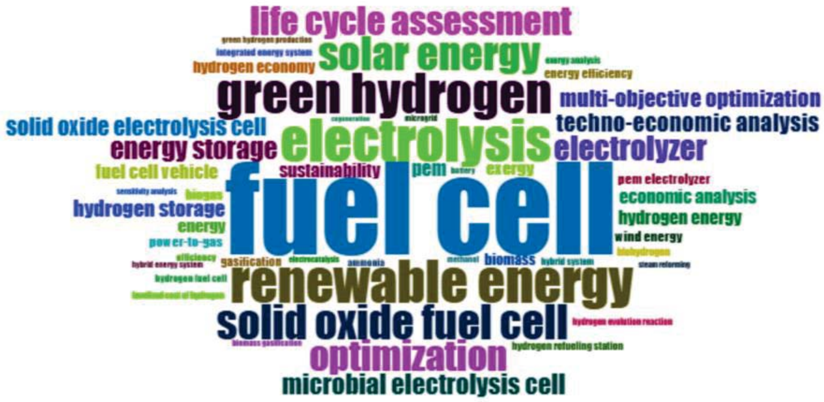

Fig. 15. Partnership between countries. (Elaborated through the Bibliometrix software).

• Publications per Year

The annual distribution of publications reveals a clear exponential growth in scientific interest regarding hydrogen production and fuel cell electric vehicles over the past decade. In 2015, only 56 publications were recorded on the topic, while in 2024, this number rose to 342, representing a more than sixfold increase (see Fig. 16).

This rising trend highlights the growing relevance of hydrogen technologies in the global energy landscape. The steady increase in publications reflects expanding research efforts, technological innovation, and international commitment to low-carbon solutions.

It is important to note that the number of publications in 2025 appears lower due to the data collection being conducted in July 2025. Therefore, the year's total output is not yet complete, and the apparent decline does not reflect a drop in interest or activity in the field.

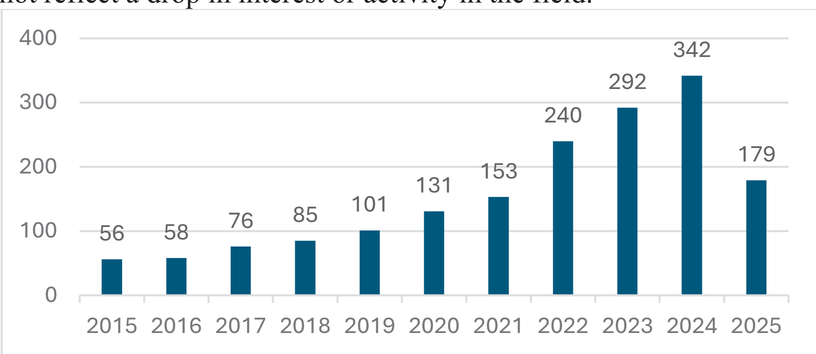

Fig. 16. Number of publications for each year. (Chart produced in Microsoft Excel).

• Publications by Country

The analysis of publications by country reveals a strong global engagement with hydrogen production and fuel cell electric vehicles, led predominantly by Asian nations (see Fig. 17). China stands out as the most prolific contributor, with 928 publications, followed by the United States (336), India (242), and South Korea (216). These countries demonstrate sustained investment and research interest in hydrogen-related technologies.

Brazil, despite having a comparatively smaller number of publications (53 articles), plays a notable role in the field. Given its vast renewable energy potential, particularly from wind, solar, and hydroelectric sources, Brazil is well-positioned to become a key player in green hydrogen production. Its scientific contributions, though numerically lower, are strategically important in advancing sustainable hydrogen initiatives in the Global South.

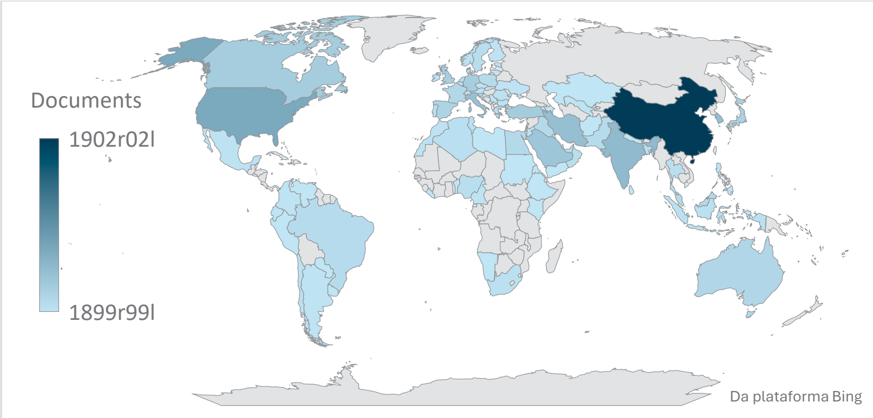

Fig. 17. Number of publications by Country. (Chart produced in Microsoft Excel).

• Publications by Journal

The distribution of publications by source highlights the International Journal of Hydrogen Energy as the leading platform for disseminating research on hydrogen production and fuel cell electric vehicles over the past decade. Its dominance reflects the journal's specialization and centrality in the field.

Other notable journals include Energy Conversion and Management, which frequently publishes high-impact articles on energy efficiency, hydrogen technologies, and sustainability transitions. These sources serve as primary hubs for scholarly communication and technological advancement in the hydrogen sector. The full visualization of the most productive sources is presented below (see Fig. 18.).

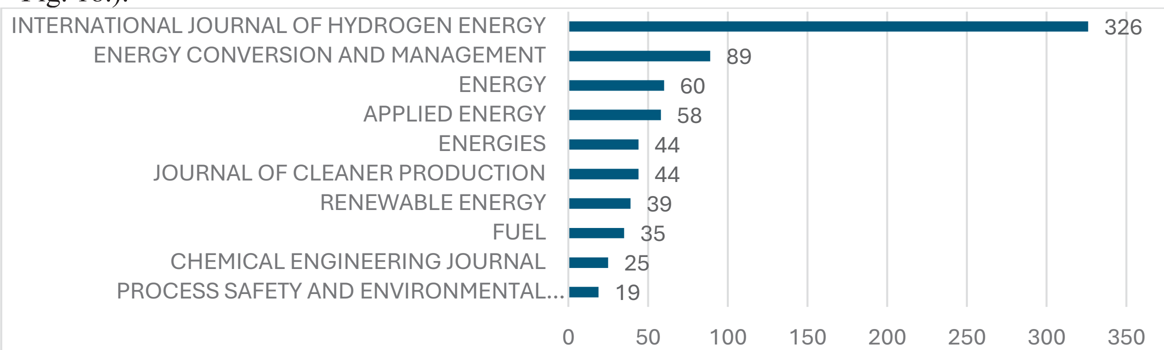

Fig. 18. Number of publications of the most relevant journals. (Chart produced in Microsoft Excel).

Systematic Review

The second part of the analysis consists of a systematic review using the PRISMA method, focusing on the 10 most cited articles identified in the bibliometric study. The selected articles, listed and summarized in Appendix A, were qualitatively evaluated to explore in greater depth the technological and strategic aspects of hydrogen-powered electric vehicles. This evaluation addressed specific research questions designed to complement the quantitative findings from Bibliometrix.

1. What technology was used for hydrogen production?

The predominant technologies were Steam Methane Reforming (SMR) and Water Electrolysis, both frequently cited in keywords and texts, highlighting their central role in research. SMR is more economically viable but environmentally harmful, while electrolysis, especially with renewable energy, is viewed as the most sustainable long-term solution [5].

2. What was the feedstock used?
Water and natural gas were the main feedstocks, aligning with electrolysis and SMR, respectively. Some articles also mentioned coal, though less frequently, due to its high environmental impact [2]. These findings reflect the global scenario and are consistent with the bibliometric data.
3. Is it related to fuel cell electric vehicles?
Only a few articles directly addressed Fuel Cell Electric Vehicles (FCEVs). Most focused on hydrogen production or integration into broader energy systems. Several articles indicated hydrogen's potential for heavy-duty and long-distance transport [6]. This complements the bibliometric analysis, where "fuel cell" and "vehicle" were common but not always central keywords.
4. What source of electricity (fossil or renewable) was used in the process?
Most articles reported continued reliance on fossil fuels, especially natural gas, due to cost advantages [7]. However, many emphasized transitioning to renewables to reduce emissions, particularly in regions with high renewable potential, an aspect also reflected in the bibliometric review.
5. Were any EESG factors mentioned?
Environmental concerns were the most discussed, especially the reduction of greenhouse gas emissions through hydrogen-powered vehicles [8]. Economic aspects were also emphasized, particularly the cost differences between production methods (SMR being cheapest and most polluting). Some studies predicted hydrogen could replace fossil fuels by 2050, especially with renewables [5]. Governance was mentioned in a few studies, focusing on regulatory and tax incentives [9]. Social aspects, however, were not addressed.

FINAL CONSIDERATIONS

The results of this study show that research on hydrogen-powered electric vehicles has significantly advanced over the last decade, with China leading the scientific output, followed by the United States and India. The International Journal of Hydrogen Energy was the most prominent publication source. Among the main production technologies identified, Steam Methane Reforming (SMR) remains the most used, but electrolysis powered by renewable energy is increasingly emphasized due to its environmental benefits.

The systematic review (Appendix A) confirmed the prevalence of natural gas and water as primary feedstocks and revealed that most studies still focus on hydrogen production, with limited attention to its direct application in fuel cell electric vehicles. Additionally, although environmental and economic aspects are frequently discussed, social and governance issues are scarcely addressed.

To accelerate the adoption of hydrogen-powered vehicles, it is crucial to expand renewable-based electrolysis infrastructure, implement supportive regulations and incentives, promote international cooperation, and invest in research on social and policy aspects [10]. These actions are key to enabling a cleaner and more sustainable transport future.

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Title (Reference)	**Keywords**	**(I) What technology was used for hydrogen production?**	**(II)What was the feedstock used?**	**(III) Is it related to fuel cell electric vehicles?**	**(IV) What source of electricity (fossil or renewable) was used in the process?**	**(V) Were any EESG factors mentioned? If so, which ones?**
A comparative technoeconomic analysis of renewable hydrogen production using solar energy [6]	-	Photoelectrochemical (PEC), photovoltaic-electrolytic (PV-E) and steam reforming (SR)	Water	Yes	Solar energy (renewable) and natural gas (fossil)	Yes - Environmental (avoided CO_2 emissions); Economic (plant-level cost analysis) and Governance (need for green H_2 support policies)
Clean energy and the hydrogen economy [1]	Hydrogen; Energy; Fuel cell	Steam methane reforming (SMR) with carbon capture and sequestration (CCS) and water electrolysis	Water and natural gas	Yes	Solar energy (renewable), wind energy (renewable) and natural gas (fossil)	Yes - Environmental (descarbonization); Governance (public–private partnerships)
Large-scale hydrogen production via water electrolysis: a techno-economic and environmental assessment [7]	-	Water electrolysis	Water	No	Solar energy (renewable) and wind energy (renewable)	Yes - Environmental (descarbonization and LCA) and Economic (current and future hydrogen production costs)

Large-vscale hydrogen production and storage technologies: Current status and future directions [5]	Hydrogen production; Hydrogen storage; Renewable energy; Underground hydrogen storage; Metal hydrides	Gasification, steam reforming, water electrolysis, thermolysis, biochemical and thermochemical	Water and natural gas	Yes	Solar energy (renewable), wind energy (renewable), geothermnal energy (renewable), solar thermal (renewable), biomass (renewable) and natural gas (fossil)	Yes - Environmental (descarbonization)
Power to gas: Technological overview, systems analysis and economic assessment for a case study in Germany [9]	Power to gas; Excess energy; Electrolysis; Methanation; Renewable energy concept; Fuel cell vehicles	Alkaline water electrolysis and high-temperature water electrolysis	Water	Yes	Solar energy (renewable) and wind energy (renewable)	Yes - Economic (FCEVs have economic potential)

Appendix A

Table A6. PRISMA meta-analysis of documents on the feasibility of hydrogen-powered electric vehicles.

Table A7. PRISMA meta-analysis of documents on the feasibility of hydrogen-powered electric vehicles. (continuation).

Title (Reference)	**Keywords**	**(I) What technology was used for hydrogen production?**	**(II)What was the feedstock used?**	**(III) Is it related to fuel cell electric vehicles?**	**(IV) What source of electricity (fossil or renewable) was used in the process?**	**(V) Were any EESG factors mentioned? If so, which ones?**
Energy-saving hydrogen production by chlorinefree hybrid seawater splitting coupling hydrazine degradation [8]	-	Water electrolysis	Water	No	Solar energy (renewable)	Yes - Environmental (avoided emissions)
Photocatalytic solar hydrogen production from water on a 100-m^2 scale [11]	-	Photocatalysis and electrolysis	Water	No	Solar energy (renewable) and wind energy (renewable)	No
Techno-economic analysis of a stand-alone hybrid renewable energy system with hydrogen production and storage options [12]	Renewable energy; Cost assessment; Electricity; Hydrogen production	Water electrolysis	Water	No	Solar energy (renewable) and wind energy (renewable)	No

The economics and the environmental benignity of different colors of hydrogen [2]	Hydrogen production; Cost investigation; Environmental analysis; Vehicle deployment	Steam reforming of natural gas or coal gasification, steam methane reforming with CCS, using natural gas or biomass, water electrolysis, microbial electrolysis and pyrolysis	Water, natural gas and coal	Yes	Solar energy (renewable), wind energy (renewable), biomass (renewable), coal (fossil) and natural gas (fossil)	Yes - Environmental (descarbonization) and Economic (FCEVs have economic potential)
The environmental performance of current and future passenger vehicles: Life cycle assessment based on a novel scenario analysis framework [10]	Life Cycle Assessment (LCA); Passenger vehicles; Environmental performance; Vehicle modeling	Steam reforming, water electrolysis	Water and natural gas	Yes	Natural gas (fossil)	Yes - Environmental (counter potential environmental drawbacks)

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INTERNATIONAL OBSERVATORY FOR INNOVATION IN LOW-CARBON ENERGY: A PLATFORM FOR MAPPING STARTUPS, SPIN-OFFS, AND STRATEGIC INVESTMENTS IN THE IBERO-AMERICAN ENERGY TRANSITION

Ricardo Nascimento Ferreira e Paula Cristina Afonso dos Santos Ferreira.

Resumo

A transição energética global demanda não apenas avanços tecnológicos, mas também novos arranjos institucionais que favoreçam a inovação colaborativa e a sustentabilidade. Neste contexto, o presente artigo propõe a criação de um Observatório Internacional de Inovação em Energias de Baixo Carbono, ancorado no modelo teórico da Hélice Quádrupla da Inovação, que integra universidade, governo, setor produtivo e sociedade civil. A proposta visa mapear e analisar startups, spin-offs universitárias e iniciativas institucionais voltadas para o desenvolvimento de tecnologias como hidrogênio verde, eletrificação e captura e uso de carbono (CCUS), no âmbito da cooperação luso-brasileira e ibero-americana. A partir de uma metodologia exploratória e qualitativa, estruturada em fases de mapeamento, sistematização e disseminação de dados, o artigo busca demonstrar como a consolidação de uma plataforma digital colaborativa pode fortalecer redes de inovação, subsidiar políticas públicas baseadas em evidências e fomentar a internacionalização de soluções sustentáveis. O trabalho contribui para ampliar a maturidade institucional e tecnológica dos ecossistemas de inovação energética, promovendo uma transição justa e participativa.

Palavras-chave: Inovação energética; Hélice Quádrupla; Hidrogênio verde; Startups; Cooperação ibero-americana; Observatório tecnológico; Transição energética.

Abstract

The global energy transition requires not only technological advancements but also new institutional arrangements that foster collaborative innovation and sustainability. In this context, this article proposes the creation of an International Observatory for Innovation in Low-Carbon Energy, grounded in the Quadruple Helix Innovation Model, which integrates universities, government, the productive sector, and civil society. The proposal aims to map and analyze startups, university spin-offs, and institutional initiatives focused on the development of technologies such as green hydrogen, electrification, and carbon capture, utilization, and storage (CCUS), within the scope of Luso-Brazilian and Ibero-American cooperation. Based on an exploratory and qualitative methodology—structured in phases of mapping, systematization, and data dissemination—the article demonstrates how the consolidation of a collaborative digital platform can strengthen innovation networks, support evidence-based public policies, and foster the internationalization of sustainable solutions. This work contributes to enhancing the institutional and technological maturity of energy innovation ecosystems, promoting a just and inclusive transition.

Keywords:Energy innovation; Quadruple Helix; Green hydrogen; Startups; Ibero-American cooperation; Technological observatory; Energy transition.

Introdução

A intensificação da crise climática, impulsionada pelas emissões de gases de efeito estufa, tem exigido transformações urgentes nos sistemas energéticos globais. Segundo o IPCC (2023), limitar o aquecimento global a 1,5 °C requer ações coordenadas e inovadoras, especialmente na descarbonização da matriz energética. Tecnologias como o hidrogênio de baixo carbono, a eletrificação de setores produtivos e os sistemas de captura e uso de carbono (CCUS) surgem como soluções estratégicas para uma transição energética justa e sustentável (IEA, 2022; European Commission, 2023).

No aspecto técnico, essas soluções carregam potencial para impulsionar transformações institucionais e produtivas, criando novas cadeias de valor e promovendo inovação orientada por missões públicas (Mazzucato, 2021). No entanto, a consolidação de ecossistemas de inovação robustos ainda enfrenta entraves estruturais na Ibero-América, como a baixa articulação entre universidades, empresas, governos e sociedade civil (Cassiolato et al., 2022; BID, 2021).Embora existam programas e redes pontuais, observa-se a ausência de plataformas integradas de gestão e monitoramento da inovação em energias de baixo carbono. A fragmentação dos dados e a falta de cooperação transnacional reduzem a eficácia das políticas públicas e limitam o avanço de startups, spin-offs e parcerias científicas em áreas estratégicas (OCDE, 2023; Andrade & Almeida, 2020).

Diante disso, este artigo tem como objetivo propor um modelo conceitual e metodológico de um Observatório Internacional de Inovação em Energias de Baixo Carbono, voltado ao mapeamento, análise e articulação de iniciativas na Ibero-América. Fundamentado na abordagem da Hélice Quádrupla da Inovação (Carayannis & Campbell, 2009), o observatório busca integrar dados, atores e estratégias de forma colaborativa e digital, contribuindo para fortalecer os ecossistemas de inovação energética entre Brasil, Portugal e demais países ibero-americanos.As contribuições deste estudo se dividem em quatro dimensões: (1) teórica, ao aplicar a hélice quádrupla no contexto energético; (2) metodológica, ao propor uma estrutura de observatório com base em TRL, fontes de fomento e tipologia de atores; (3) prática, ao indicar rotas de articulação entre universidades, startups, governos e comunidades; e (4) estratégica, ao oferecer subsídios para políticas públicas baseadas em evidências. O artigo se estrutura em cinco seções: introdução, fundamentação teórica, metodologia, proposta do observatório e considerações finais.

2. FUNDAMENTAÇÃO TEÓRICA

A criação de um Observatório Internacional de Inovação em Energias de Baixo Carbono requer uma base teórica que reflita a complexidade da transição energética e a integração de múltiplos atores institucionais. Essa transição, impulsionada pelo Acordo de Paris e pelos alertas do IPCC (2023), exige cortes de 43% nas emissões globais até 2030, com tecnologias como hidrogênio de baixo carbono, eletrificação e CCUS responsáveis por cerca de 35% dessas reduções até 2050 (IEA, 2022).

Nesse contexto, a inovação energética deve ser vista como um processo sistêmico, interativo e orientado por missões públicas. A fundamentação teórica deste estudo estrutura-se em quatro eixos: (1) a evolução dos modelos de inovação, da Tríplice à Quíntupla Hélice (Etzkowitz & Leydesdorff, 2000; Carayannis & Campbell, 2012; Carayannis & Grigoroudis, 2022); (2) o papel ativo da sociedade civil na coprodução de soluções energéticas locais (OECD, 2023; Silva et al., 2022); (3) os ecossistemas de inovação aberta e a governança em rede com apoio de plataformas digitais (Chesbrough & Bogers, 2022; BID, 2021); e (4) os sistemas locais de inovação e as abordagens orientadas por missões públicas (Mazzucato, 2021; Cassiolato et al., 2022).Esses eixos sustentam a proposta do observatório como ferramenta de inteligência estratégica e cooperação internacional para o avanço da inovação em energias limpas.

2.1 Evolução dos Modelos de Inovação: Da Tríplice à Hélice Quádrupla

A inovação, por muito tempo, foi vista como um processo linear, restrito a laboratórios e empresas, com foco na transferência unidirecional do conhecimento da ciência para o mercado (Godin, 2006). Essa visão começou a mudar nas décadas de 1980 e 1990, com o surgimento de abordagens que destacam a dimensão interativa e institucional da inovação, reconhecendo sua produção em redes complexas.

Nesse cenário, Etzkowitz e Leydesdorff (2000) propuseram a Tríplice Hélice, modelo que articula universidade, empresa e governo em um ecossistema de inovação. A partir dos desafios contemporâneos, como a crise climática, Carayannis e Campbell (2009, 2012) ampliaram esse modelo com a Hélice Quádrupla, inserindo a sociedade civil como agente ativo na coprodução e validação das inovações. Mais recentemente, a Quíntupla Hélice propõe a inclusão da dimensão ambiental como eixo estruturante da inovação (Carayannis & Grigoroudis, 2022). No contexto das energias de baixo carbono, essa abordagem justifica a criação de observatórios multissetoriais que integrem dados, atores e políticas para acelerar a transição energética de forma socialmente legítima e sustentável (Mazzucato, 2021; Cassiolato et al., 2022).

2.2 O Papel da Sociedade Civil e da Coprodução do Conhecimento

A participação da sociedade civil nos ecossistemas de inovação representa uma mudança significativa nas políticas de ciência e tecnologia. De coadjuvante, ela passa a ser reconhecida como coprodutora de conhecimento, contribuindo com saberes locais, demandas sociais e valores ambientais. Essa perspectiva está alinhada à inovação orientada por missões, que propõe o engajamento coletivo na definição de prioridades científicas (Mazzucato, 2021; Comissão Europeia, 2022).

Entre 2020 e 2025, estudos na América Latina evidenciam o protagonismo de comunidades em projetos de energia limpa, como iniciativas de hidrogênio verde e energia solar comunitária no Brasil, Chile e Colômbia. Essas ações, em territórios vulneráveis, exigem governança transparente e distribuição justa de benefícios (Silva et al., 2022; Torres & Carvalho, 2023). Segundo a OCDE (2023), a inclusão ativa da sociedade civil fortalece a legitimidade e a resiliência dos projetos de transição energética. As ferramentas como observatórios tecnológicos, plataformas colaborativas e fóruns participativos têm sido eficazes na integração entre ciência e sociedade, permitindo o uso combinado de dados técnicos e percepções sociais na formulação de políticas públicas (Andrade & Almeida, 2020; UNESCO, 2021). Esses instrumentos viabilizam uma governança mais inclusiva e adaptada às realidades locais.As evidências do Banco Mundial (2022) mostram que iniciativas com cogestão comunitária têm maior continuidade e impacto. Isso reforça a necessidade de incorporar sistematicamente a sociedade civil nos processos decisórios da inovação energética, consolidando seu papel como agente estratégico da transição sustentável.

2.3 Inovação Aberta, Ecossistemas de Energia Limpa e Governança em Rede

Diante da complexidade crescente dos desafios energéticos e climáticos, modelos tradicionais de inovação se mostram insuficientes. A inovação aberta, proposta por Chesbrough (2003) e atualizada por Chesbrough e Bogers (2022), destaca-se por incentivar a colaboração entre universidades, empresas, governos e sociedade civil na criação conjunta de soluções tecnológicas.

No setor energético, essa abordagem tem sido aplicada ao desenvolvimento de tecnologias como hidrogênio verde, eletrificação industrial e sistemas de captura e uso de carbono (CCUS). Segundo a IEA (2022), tais iniciativas exigem ecossistemas com governança em rede e plataformas digitais que rastreiem projetos, avaliem o nível de maturidade tecnológica (TRL) e integrem parcerias multissetoriais. Para Cassiolato et al. (2022), esses sistemas devem ser abertos, coordenados e baseados na confiança entre os atores envolvidos.

Para Ribeiro et al. (2023) reforçam que fluxos contínuos de informação e clareza institucional são cruciais para garantir agilidade e legitimidade nas decisões. Diferente dos modelos hierárquicos, a governança em rede privilegia inteligência coletiva e flexibilidade — aspectos fundamentais para a transição energética. Nesse contexto, observatórios tecnológicos surgem como instrumentos estratégicos. Eles apoiam políticas públicas baseadas em evidências, fortalecem redes de inovação e integram dados técnicos e territoriais. Alinhados aos ODS 7, 9 e 13, tais observatórios contribuem para soluções energéticas mais inclusivas, sustentáveis e adaptadas às realidades locais (UNESCO, 2021; Soares & Prado, 2022; ONU, 2023; UNCTAD, 2022).

2.4 Estudos Recentes Aplicados à Inovação Energética

A produção científica recente sobre inovação energética tem enfatizado abordagens interativas, multiescalares e orientadas por missões públicas. No Brasil, Cassiolato, Lastres e Matos (2022) destacam os sistemas locais de inovação como fundamentais para o desenvolvimento de tecnologias limpas adaptadas às realidades regionais. Mazzucato (2021) defende o protagonismo do Estado em inovações guiadas por metas sociais e ambientais. Carayannis e Grigoroudis (2022) reforçam a importância de uma abordagem sistêmica e transdisciplinar para energias de baixo carbono.

Essas perspectivas têm orientado organismos como o BID (2021), a OCDE (2023) e a UNCTAD (2022), que recomendam a criação de estruturas digitais de monitoramento como observatórios para fomentar a descarbonização com base em dados e participação social.Na Ibero-América, a parceria entre Portugal e Brasil avança na agenda de inovação energética. As estratégias nacionais de ambos os países para o hidrogênio de baixo carbono, alinhadas por meio de um memorando assinado em 2023, preveem cooperação em governança, formação e tecnologias (MCTI, 2023; Ministério do Ambiente e Ação Climática de Portugal, 2022).

Nesse cenário, propõe-se a criação de um Observatório Internacional Luso-Brasileiro de Inovação Energética, que atue como plataforma estratégica para mapear startups, centros de pesquisa e políticas públicas voltadas ao hidrogênio verde. Com base em dados georreferenciados, análises comparativas e cooperação multissetorial, o observatório visa fortalecer ecossistemas de inovação aberta, conectados e sustentáveis (UNESCO, 2021; Soares & Prado, 2022; European Commission, 2023).

3. Metodologia

Este estudo adota uma abordagem exploratória, qualitativa e sistêmica, adequada à análise de fenômenos complexos e emergentes, como a cooperação multissetorial na inovação em energias de baixo carbono. A escolha é justificada pela ausência de instrumentos integrados que articulem atores, dados e iniciativas no contexto luso-brasileiro. Conforme Gil (2023), a pesquisa exploratória permite mapear temas pouco estudados e formular propostas inovadoras, enquanto a abordagem qualitativa favorece a compreensão de relações sociais e institucionais (Minayo, 2021; Godoy, 2020).

A metodologia baseia-se em levantamento de dados secundários oriundos de fontes confiáveis, como IEA, OCDE, Comissão Europeia, BID, MCTI (Brasil) e Ministério do Ambiente (Portugal), abrangendo documentos técnicos, políticas públicas, projetos financiados e estudos entre 2020 e 2025. A seleção desses dados atende aos critérios de confiabilidade, relevância e aderência temática (Yin, 2021).Como resultado, propõe-se a criação de uma plataforma digital em formato de observatório internacional, voltado ao mapeamento e articulação de iniciativas e atores ligados à inovação energética. A estrutura do observatório será fundamentada na hélice quádrupla da inovação (Carayannis & Campbell, 2012), integrando academia, governo, setor produtivo e sociedade civil.

A análise sistêmica será orientada por quatro critérios principais: (i) Nível de Maturidade Tecnológica (TRL); (ii) Fontes de financiamento (públicas, privadas ou híbridas); (iii) Tipologia dos atores (segundo a hélice quádrupla); e (iv) Escopo dos projetos (local, nacional ou transnacional, com foco nas cooperações Brasil–Portugal e Ibero-América). A triangulação entre dados, teoria e objetivos permitirá identificar padrões e lacunas, apoiando o desenvolvimento de uma plataforma colaborativa, atualizável e estratégica para a governança da transição energética.

3.1. Proposta do Observatório Internacional de Inovação em Energias de Baixo Carbono

Diante dos crescentes desafios da transição energética e da necessidade de fortalecer estruturas de cooperação internacional, este artigo propõe a criação de um Observatório Internacional de Inovação em Energias de Baixo Carbono**,** com foco na articulação entre Brasil e Portugal. A proposta visa suprir uma lacuna crítica de governança e integração de informações estratégicas sobre tecnologias emergentes como hidrogênio verde, eletrificação de setores produtivos e sistemas de captura, uso e armazenamento de carbono (CCUS), considerando as metas do Acordo de Paris e os compromissos da Agenda 2030.

O objetivo geral do observatório **é** mapear, articular e promover a colaboração multissetorial em projetos e políticas de inovação energética de baixo carbono, envolvendo universidades, centros de pesquisa, empresas, governos e organizações da sociedade civil. Especificamente, o observatório buscará organizar dados sobre tecnologias em desenvolvimento, consolidar uma base de conhecimento acessível e promover a criação de parcerias transnacionais para projetos conjuntos de pesquisa e inovação. A expectativa é que, ao facilitar o acesso a informações qualificadas e oportunidades de colaboração, o observatório fortaleça o ecossistema de inovação em ambos os países.

Para Portugal**,** a implementação do observatório representa uma oportunidade de ampliar sua posição como hub estratégico de hidrogênio verde no Atlântico, consolidando seu papel no mercado europeu de energias renováveis. De acordo com a ADENE (2023), o país possui potencial logístico, político e técnico para exportar hidrogênio verde para países da União Europeia, sobretudo em parcerias com nações do Sul Global. Já para o Brasil, o observatório pode ser um instrumento-chave para internacionalizar o conhecimento produzido por universidades e startups energéticas, além de atrair investimentos verdes e impulsionar a diplomacia científica e tecnológica (MCTI, 2024; ApexBrasil, 2023). A estrutura funcional do observatório será baseada em uma plataforma digital interativa, desenvolvida em parceria com universidades e centros de pesquisa de excelência nos dois países, como a Universidade Federal do Rio de Janeiro (UFRJ), a Universidade de Lisboa e o INESC TEC. Essa plataforma terá como usuários-alvo pesquisadores, empresas de base tecnológica, órgãos públicos, agências de fomento, investidores, organizações não governamentais e coletivos ligados à energia e ao meio ambiente. O ambiente digital contará com funcionalidades como filtros por tipo de tecnologia, nível de maturidade tecnológica (TRL), fonte de financiamento, tipologia dos atores envolvidos e localização geográfica dos projetos.

A plataforma será construída com uma base de dados colaborativa, alimentada por meio de parcerias institucionais e de chamadas públicas para registro de iniciativas, garantindo constante atualização. Estão previstas interfaces para acesso público e para áreas restritas com funcionalidades avançadas, como criação de consórcios, elaboração de relatórios personalizados e lançamento de editais conjuntos. A governança do observatório será compartilhada por um consórcio Brasil–Portugal, com representantes técnicos, acadêmicos e institucionais, que se reunirão periodicamente para avaliar a plataforma, definir critérios de categorização e validar informações.Para garantir o dinamismo e a relevância da proposta, o observatório integrará mecanismos de atualização contínua, como oficinas participativas, fóruns híbridos (virtuais e presenciais), consultas públicas e comitês técnico-científicos. A adesão a princípios de ciência aberta, transparência e governança em rede será central para fomentar a confiança entre os diferentes atores e valorizar o conhecimento gerado em contextos locais e regionais. Essa dinâmica colaborativa segue as diretrizes recomendadas pela OCDE (2023) e por experiências bem-sucedidas como o European Energy Research Alliance (EERA) e o Energy Innovation Observatory (EIO), que já operam com foco em inteligência territorial e inovação verde.

Serão estabelecidos indicadores de desempenho e impacto, com o objetivo de monitorar e avaliar os resultados obtidos pela iniciativa ao longo do tempo. Esses indicadores incluirão o número de projetos mapeados, a quantidade de parcerias institucionais firmadas, o volume de dados acessados na plataforma, o número de startups e spin-offs identificadas, o total de iniciativas bilaterais ativas entre Brasil e Portugal, e estimativas de redução de emissões de CO_2 associadas às tecnologias observadas. A medição contínua desses indicadores permitirá ajustes estratégicos e dará subsídios a formuladores de políticas públicas e investidores interessados em apoiar a transição energética justa e sustentável. O Observatório Internacional de Inovação em Energias de Baixo Carbono configura-se como uma proposta estratégica de elevada relevância, capaz de conectar ciência, política e sociedade por meio de uma arquitetura institucional moderna e inclusiva. Ele responde à necessidade de ampliar a maturidade institucional da inovação energética em países com elevado potencial científico e tecnológico, promovendo a internacionalização de soluções sustentáveis, o fortalecimento da governança em rede e a democratização do acesso ao conhecimento.

3.2. Comparação com Observatórios Internacionais Existentes

A criação de um Observatório Internacional de Inovação em Energias de Baixo Carbono no eixo Brasil–Portugal se inspira em modelos internacionais bem-sucedidos, mas também preenche uma lacuna específica no contexto ibero-americano. A seguir, são analisadas algumas das experiências mais relevantes:

Observatório / Instituição	**País / Região**	**Foco Principal**	**Características**	**Limitações**
IEA Hydrogen TCP – International Energy Agency	Multinacional (OCDE)	Cooperação técnica e P&D em hidrogênio de baixo carbono	Rede governamental de especialistas; projetos técnicos e padronização	Baixa interface com startups e sociedade civil

Energy Innovation Observatory (EIO) – Uppsala University	Suécia / Europa	Análise de políticas públicas e tendências de inovação energética	Foco acadêmico e regulatório; forte base de dados públicos	Restrito à realidade europeia e limitado à dimensão institucional governamental
GO-P2P – Global Observatory on Peer-to-Peer Energy Models (UCL)	Reino Unido	Modelos descentralizados e justiça energética	Ênfase em participação comunitária e modelos distributivos	Foco apenas em consumo e transações locais
OLADE / Observatório Energético Latino-Americano (UNASUR)	Equador / América Latina	Planejamento energético regional e estatísticas do setor	Coleta de dados técnicos de 27 países-membros	Pouca articulação com inovação e tecnologia; foco estatístico centralizado
Observatório Internacional de Inovação em Energias de Baixo Carbono (Proposta)	Brasil–Portugal / Ibero-América	Inovação tecnológica em hidrogênio, CCUS e energias limpas	Plataforma interativa, cooperação binacional, dados abertos, TRL, sociedade civil, governança em rede	Diferencial estratégico: inovação aberta + integração de hélice quádrupla + cooperação Sul–Norte e ibero-americana

Fonte: Elaborado pelo autor

4. Resultados Esperados e Contribuições

A proposta de criação de um Observatório Internacional de Inovação em Energias de Baixo Carbono projeta uma série de resultados esperados e contribuições práticas e acadêmicas, capazes de fortalecer o ecossistema ibero-americano de ciência, tecnologia e inovação voltado à transição energética sustentável. A seguir, detalham-se os principais eixos de impacto previstos.

No primeiro eixo, espera-se a consolidação de uma base estratégica de dados e informações qualificadas sobre inovação energética na Ibero-América. A ausência de plataformas integradas que organizem, georreferenciem e analisem projetos, tecnologias, atores e fontes de financiamento tem sido um entrave à tomada de decisão baseada em evidências. Ao reunir dados de diversas instituições, o observatório poderá gerar inteligência coletiva, permitindo identificar lacunas, oportunidades e sinergias entre os países da região. No segundo eixo, a iniciativa contribuirá diretamente para o apoio à formulação de políticas públicas, programas de fomento e estratégias empresariais em energias limpas. Governos e agências de inovação poderão acessar informações sistematizadas sobre maturidade tecnológica (TRL), viabilidade comercial, adesão social e impactos ambientais dos projetos em andamento. Essa infraestrutura de dados permitirá o desenho de mecanismos de financiamento mais eficazes, priorizando soluções inovadoras com alto potencial de impacto social e ambiental. No terceiro eixo, destaca-se o fortalecimento da cooperação internacional entre instituições luso-brasileiras e ibero-americanas. Ao funcionar como uma interface digital colaborativa, o observatório facilitará a formação de consórcios transnacionais, a mobilização de recursos internacionais e a construção de agendas comuns de pesquisa e inovação. Tal articulação reforça os princípios da diplomacia científica e tecnológica e amplia a inserção internacional das universidades, centros de pesquisa e startups dos países envolvidos.

A proposta contribui para a promoção de uma transição energética mais participativa, inclusiva e sustentável, ao reconhecer o papel ativo da sociedade civil no processo de coprodução do conhecimento. A disponibilização de dados públicos, a promoção de fóruns interativos e a incorporação de indicadores sociais e territoriais na análise dos projetos permitirá uma governança mais democrática, transparente e sensível às desigualdades regionais. Em conjunto, esses resultados reforçam a relevância do observatório como instrumento de inovação institucional e tecnológica, com potencial de catalisar transformações sistêmicas nos modelos de produção e uso de energia no espaço ibero-americano.

CONSIDERAÇÕES FINAIS

A proposta de criação de um Observatório Internacional de Inovação em Energias de Baixo Carbono entre Brasil e Portugal representa uma resposta estratégica às crescentes demandas por modelos colaborativos, sustentáveis e orientados por dados na condução da transição energética. Ao longo deste artigo, demonstrou-se a relevância de se adotar uma abordagem sistêmica da inovação, alicerçada no modelo da Hélice Quádrupla, que reconhece a interdependência entre universidades, empresas, governos e sociedade civil na coprodução de soluções para desafios socioambientais globais. Essa visão amplia os horizontes tradicionais da inovação tecnológica e insere a energia limpa no centro das transformações institucionais, econômicas e culturais do século XXI.

Entre as principais contribuições práticas do estudo, destaca-se o desenho de uma estrutura funcional para o observatório, capaz de consolidar uma base estratégica de dados, promover a cooperação internacional e articular atores diversos em uma plataforma digital interativa. A proposta oferece instrumentos concretos para subsidiar políticas públicas, apoiar decisões empresariais e fomentar a inovação aberta, em especial no campo do hidrogênio verde, da eletrificação e das tecnologias de captura e uso de carbono (CCUS). Além disso, reforça a importância da governança em rede e da transparência como princípios estruturantes da nova economia de baixo carbono, alinhada às metas do Acordo de Paris e da Agenda 2030.

No entanto, a implementação de um observatório dessa natureza não está isenta de desafios. Entre as limitações identificadas, figuram a heterogeneidade dos sistemas nacionais de inovação, a disponibilidade desigual de dados abertos, os entraves legais para compartilhamento de informações e a resistência institucional à inovação participativa. Superar esses obstáculos exigirá compromissos políticos, investimentos continuados e o fortalecimento de capacidades técnicas e colaborativas entre os países envolvidos.

Este estudo abre espaço para pesquisas futuras que aprofundem a viabilidade técnica, jurídica e financeira da plataforma proposta, bem como para investigações empíricas sobre os impactos de observatórios semelhantes em outros setores estratégicos da transição verde — como agricultura regenerativa, economia circular e mobilidade sustentável. Recomenda-se ainda a realização de estudos comparativos internacionais e o desenvolvimento de indicadores de impacto que permitam avaliar a efetividade do observatório na indução de inovações sustentáveis e socialmente legitimadas. Conclui-se que a proposta aqui delineada, embora inicial, oferece um caminho promissor para consolidar pontes entre ciência, sociedade e política, contribuindo para uma transição energética justa, colaborativa e baseada no conhecimento.

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INTERNATIONAL OBSERVATORY FOR INNOVATION IN LOW-CARBON ENERGY: A PLATFORM FOR MAPPING STARTUPS, SPIN-OFFS, AND STRATEGIC INVESTMENTS IN THE IBERO-AMERICAN ENERGY TRANSITION

Ricardo Nascimento Ferreira e Paula Cristina Afonso dos Santos Ferreira

Resumo

A transição energética global demanda não apenas avanços tecnológicos, mas também novos arranjos institucionais que favoreçam a inovação colaborativa e a sustentabilidade. Neste contexto, o presente artigo propõe a criação de um Observatório Internacional de Inovação em Energias de Baixo Carbono, ancorado no modelo teórico da Hélice Quádrupla da Inovação, que integra universidade, governo, setor produtivo e sociedade civil. A proposta visa mapear e analisar startups, spin-offs universitárias e iniciativas institucionais voltadas para o desenvolvimento de tecnologias como hidrogênio verde, eletrificação e captura e uso de carbono (CCUS), no âmbito da cooperação luso-brasileira e ibero-americana. A partir de uma metodologia exploratória e qualitativa, estruturada em fases de mapeamento, sistematização e disseminação de dados, o artigo busca demonstrar como a consolidação de uma plataforma digital colaborativa pode fortalecer redes de inovação, subsidiar políticas públicas baseadas em evidências e fomentar a internacionalização de soluções sustentáveis. O trabalho contribui para ampliar a maturidade institucional e tecnológica dos ecossistemas de inovação energética, promovendo uma transição justa e participativa.

Palavras-chave: Inovação energética; Hélice Quádrupla; Hidrogênio verde; Startups; Cooperação ibero-americana; Observatório tecnológico; Transição energética.

Abstract

The global energy transition requires not only technological advancements but also new institutional arrangements that foster collaborative innovation and sustainability. In this context, this article proposes the creation of an International Observatory for Innovation in Low-Carbon Energy, grounded in the Quadruple Helix Innovation Model, which integrates universities, government, the productive sector, and civil society. The proposal aims to map and analyze startups, university spin-offs, and institutional initiatives focused on the development of technologies such as green hydrogen, electrification, and carbon capture, utilization, and storage (CCUS), within the scope of Luso-Brazilian and Ibero-American cooperation. Based on an exploratory and qualitative methodology—structured in phases of mapping, systematization, and data dissemination—the article demonstrates how the consolidation of a collaborative digital platform can strengthen innovation networks, support evidence-based public policies, and foster the internationalization of sustainable solutions. This work contributes to enhancing the institutional and technological maturity of energy innovation ecosystems, promoting a just and inclusive transition.

Keywords: Energy innovation; Quadruple Helix; Green hydrogen; Startups; Ibero-American cooperation; Technological observatory; Energy transition.

Introduction

The intensification of the climate crisis, driven by greenhouse gas emissions, demands urgent transformations in global energy systems. According to the IPCC (2023), limiting global warming to 1.5 °C requires coordinated and innovative actions, particularly the decarbonization of the energy matrix. Technologies such as low-carbon hydrogen, the electrification of productive sectors, and carbon capture, utilization, and storage (CCUS) emerge as strategic solutions for a just and sustainable energy transition (IEA, 2022; European Commission, 2023).

From a technical perspective, these solutions carry the potential to drive institutional and productive transformations, creating new value chains and fostering mission-oriented innovation (Mazzucato, 2021). However, the consolidation of robust innovation ecosystems still faces structural barriers across Ibero-America, including limited coordination among universities, businesses, governments, and civil society (Cassiolato et al., 2022; IDB, 2021). Although there are isolated programs and networks, the region lacks integrated platforms for managing and monitoring low-carbon energy innovation. Data fragmentation and weak transnational cooperation reduce the effectiveness of public policies and constrain the growth of startups, spin-offs, and scientific partnerships in strategic areas (OECD, 2023; Andrade & Almeida, 2020).

In this context, the objective of this article is to propose a conceptual and methodological model for an **International Observatory for Innovation in Low-Carbon Energy**, designed to map, analyze, and connect initiatives across Ibero-America. Grounded in the Quadruple Helix of Innovation approach (Carayannis & Campbell, 2009), the observatory seeks to integrate data, stakeholders, and strategies in a collaborative digital environment, thereby strengthening energy innovation ecosystems among Brazil, Portugal, and other Ibero-American countries. The contributions of this study unfold across four dimensions: (1) theoretical, by applying the Quadruple Helix framework to the energy context; (2) methodological, by proposing an observatory structure based on Technology Readiness Levels (TRLs), funding sources, and actor typologies; (3) practical, by identifying pathways for collaboration among universities, startups, governments, and communities; and (4) strategic, by providing evidence-based inputs for public policy. The article is organized into five sections: introduction, theoretical foundation, methodology, observatory proposal, and final considerations.

2. Theoretical Foundation

Establishing an International Observatory for Innovation in Low-Carbon Energy requires a theoretical foundation that captures the complexity of the energy transition and the integration of multiple institutional actors. This transition, driven by the Paris Agreement and IPCC (2023) warnings, calls for a 43 % reduction in global emissions by 2030, with technologies such as low-carbon hydrogen, electrification, and CCUS responsible for roughly 35 % of these reductions by 2050 (IEA, 2022).

Within this context, energy innovation must be understood as a systemic, interactive process guided by public missions. The theoretical framework of this study is structured around four key axes; (i)**Evolution of innovation models**, from the Triple to the Quintuple Helix (Etzkowitz & Leydesdorff, 2000; Carayannis & Campbell, 2012; Carayannis & Grigoroudis, 2022);(ii)**Active role of civil society** in co-producing local energy solutions (OECD, 2023; Silva et al., 2022);(iii)**Open innovation ecosystems and network governance** supported by digital platforms (Chesbrough & Bogers, 2022; IDB, 2021); and (iv)**Local innovation systems and mission-oriented approaches** to public policy (Mazzucato, 2021; Cassiolato et al., 2022).

Together, these axes underpin the proposal of the observatory as a tool for strategic intelligence and international cooperation to advance innovation in clean energy.

2.1 Evolution of Innovation Models: From the Triple to the Quadruple Helix

Innovation was long understood as a linear process confined to laboratories and firms, with a one-way flow of knowledge from science to the market (Godin, 2006). This perspective began to shift in the 1980s and 1990s as news approaches emphasized the interactive and institutional nature of innovation, recognizing its emergence within complex networks.

In this context, Etzkowitz and Leydesdorff (2000) proposed the Triple Helix model, which integrates universities, industry, and government into a collaborative innovation ecosystem. Responding to contemporary challenges such as the climate crisis, Carayannis and Campbell (2009, 2012) expanded this framework into the Quadruple Helix, incorporating civil society as an active agent in the co-production and validation of innovation. More recently, the Quintuple Helix added the environmental dimension as a core component of innovation (Carayannis & Grigoroudis, 2022).

For the field of low-carbon energy, this progression highlights the need for multisectoral observatories that integrate data, stakeholders, and policies to accelerate the energy transition in a socially legitimate and sustainable way (Mazzucato, 2021; Cassiolato et al., 2022). By positioning citizens and environmental considerations alongside academic, industrial, and governmental actors, the Quadruple/Quintuple Helix provides the conceptual basis for a collaborative platform capable of guiding evidence-based strategies for decarbonization.

2.2 The Role of Civil Society and Knowledge Co-Production

The inclusion of civil society in innovation ecosystems represents a profound shift in science and technology policy. Once seen as peripheral, civil society is now recognized as a co-producer of knowledge, contributing local expertise, social demands, and environmental values. This perspective aligns with the concept of mission-oriented innovation, which calls for collective engagement in setting scientific and technological priorities (Mazzucato, 2021; European Commission, 2022).

Between 2020 and 2025, studies across Latin America have documented the leadership of local communities in clean energy projects, including green hydrogen initiatives and community solar programs in Brazil, Chile, and Colombia. These efforts—often located in socially and economically vulnerable regions—require transparent governance and equitable distribution of benefits (Silva et al., 2022; Torres & Carvalho, 2023). According to the OECD (2023), the active participation of civil society enhances the legitimacy and resilience of energy transition projects.Technological observatories, collaborative digital platforms, and participatory forums have proven effective in bridging science and society, enabling the integration of technical data with social perceptions for evidence-based policymaking (Andrade & Almeida, 2020; UNESCO, 2021). World Bank (2022) findings further show that community co-management significantly improves the continuity and long-term impact of clean energy initiatives. These insights reinforce the necessity of systematically embedding civil society into decision-making processes for energy innovation, consolidating its role as a strategic driver of a sustainable and socially inclusive energy transition.

2.3 Open Innovation, Clean Energy Ecosystems, and Network Governance

Given the growing complexity of energy and climate challenges, traditional innovation models are proving insufficient. Open innovation, first proposed by Chesbrough (2003) and further developed by Chesbrough and Bogers (2022), stands out for promoting collaboration among universities, companies, governments, and civil society in the co-creation of technological solutions. In the energy sector, this approach has been applied to the development of low-carbon technologies such as green hydrogen, industrial electrification, and carbon capture, utilization, and storage (CCUS). According to the IEA (2022), these initiatives require ecosystems with network-based governance and digital platforms capable of tracking projects, assessing Technology Readiness Levels (TRLs), and integrating multisector partnerships. Cassiolato et al. (2022) emphasize that such systems must be open, well-coordinated, and built on trust among all stakeholders.

Ribeiro et al. (2023) add that continuous information flows and clear institutional arrangements are essential to ensure agility and legitimacy in decision-making. Unlike hierarchical models, network governance prioritizes collective intelligence and flexibility—key attributes for advancing the energy transition. Within this framework, technological observatories emerge as strategic instruments. They support evidence-based public policies, strengthen innovation networks, and integrate technical and territorial data. Aligned with SDGs 7, 9, and 13, these observatories contribute to energy solutions that are inclusive, sustainable, and responsive to local contexts (UNESCO, 2021; Soares & Prado, 2022; United Nations, 2023; UNCTAD, 2022).

2.4 Recent Studies on Energy Innovation

Recent scientific literature on energy innovation highlights interactive, multi-scalar, and mission-oriented approaches. In Brazil, Cassiolato, Lastres, and Matos (2022) underscore the importance of local innovation systems for developing clean technologies tailored to regional realities. Mazzucato (2021) argues for a proactive state role in mission-driven innovations aimed at achieving social and environmental goals. Carayannis and Grigoroudis (2022) reinforce the need for a systemic and transdisciplinary perspective when advancing low-carbon energy solutions.

These perspectives guide key international organizations such as the Inter-American Development Bank (IDB, 2021), the OECD (2023), and UNCTAD (2022), all of which recommend creating digital monitoring structures, such as observatories, to foster decarbonization through data-driven strategies and social participation.

Within Ibero-America, the Portugal–Brazil partnership exemplifies this trend. National strategies for low-carbon hydrogen in both countries were aligned through a bilateral memorandum signed in 2023, outlining cooperation in governance, workforce training, and technology development (MCTI, 2023; Portuguese Ministry of Environment and Climate Action, 2022).Against this backdrop, the proposal for an International Luso-Brazilian Observatory of Energy Innovation emerges as a strategic platform to map startups, research centers, and public policies dedicated to green hydrogen. Using georeferenced data, comparative analysis, and multisector cooperation, the observatory seeks to strengthen open, connected, and sustainable innovation ecosystems (UNESCO, 2021; Soares & Prado, 2022; European Commission, 2023).

3. Methodology

This study adopts an exploratory, qualitative, and systemic approach, suitable for analyzing complex and emerging phenomena such as multisector cooperation in low-carbon energy innovation. The choice is justified by the lack of integrated tools capable of connecting stakeholders, data, and initiatives in the Luso-Brazilian context. According to Gil (2023), exploratory research allows the mapping of under-studied topics and the formulation of innovative proposals, while a qualitative perspective supports the understanding of social and institutional relationships (Minayo, 2021; Godoy, 2020).

The methodological design is based on the collection of secondary data from reliable sources such as the International Energy Agency (IEA), the Organisation for Economic Co-operation and Development (OECD), the European Commission, the Inter-American Development Bank (IDB), Brazil's Ministry of Science, Technology and Innovation (MCTI), and Portugal's Ministry of the Environment. These sources include technical documents, public policies, funded projects, and analytical studies published between 2020 and 2025. Selection of the material followed the criteria of credibility, relevance, and thematic adherence recommended by Yin (2021).

As a result of this analysis, the study proposes the creation of a digital international observatory designed to map and articulate initiatives and stakeholders involved in energy innovation. The observatory's framework is grounded in the Quadruple Helix of Innovation (Carayannis & Campbell, 2012), integrating academia, government, industry, and civil society into a collaborative platform.

The systemic analysis is guided by four main criteria:

Technology Readiness Level (TRL) of the projects;

Funding sources, whether public, private, or hybrid;

Typology of actors, classified according to the Quadruple Helix model; and

Project scope, identifying local, national, or transnational initiatives, with a particular focus on Brazil–Portugal and broader Ibero-American cooperation.

Triangulation of data, theoretical frameworks, and research objectives supports the identification of patterns and gaps, providing the analytical foundation for a collaborative, continuously updated platform to enhance governance in the low-carbon energy transition.

3.1 Proposal for the International Observatory for Innovation in Low-Carbon Energy

Given the escalating challenges of the global energy transition and the need to strengthen international cooperation structures, this article proposes the creation of an International Observatory for Innovation in Low-Carbon Energy, with a special focus on Brazil–Portugal collaboration. The observatory aims to fill a critical governance gap and integrate strategic information on emerging technologies such as green hydrogen, industrial electrification, and carbon capture, utilization, and storage (CCUS), in line with the goals of the Paris Agreement and the UN 2030 Agenda.

The primary objective of the observatory is to map, connect, and foster multisector collaboration in energy innovation projects and policies, bringing together universities, research centers, companies, governments, and civil-society organizations. More specifically, it seeks to organize and curate data on developing technologies, consolidate an accessible knowledge base, and encourage the creation of transnational partnerships for joint research and innovation. By facilitating access to qualified information and collaboration opportunities, the observatory is expected to strengthen the energy-innovation ecosystem in both Brazil and Portugal.

For Portugal, the initiative offers an opportunity to expand its position as a strategic Atlantic hub for green hydrogen, reinforcing its role in the European renewable energy market. According to ADENE (2023), Portugal has the logistical, political, and technical capacity to export green hydrogen to EU countries, particularly in partnership with nations of the Global South. For Brazil, the observatory provides a key mechanism for the internationalization of knowledge generated by universities and energy startups, while attracting green investment and boosting scientific and technological diplomacy (MCTI, 2024; ApexBrasil, 2023).

The observatory will be implemented as an interactive digital platform, developed in partnership with leading universities and research institutions in both countries, such as the Federal University of Rio de Janeiro (UFRJ), the University of Lisbon, and INESC TEC. Intended users include researchers, technology-based companies, public agencies, funding institutions, investors, NGOs, and community groups focused on energy and the environment.

Key platform features will include filters by technology type, TRL level, funding source, actor typology, and geographical location of projects. A collaborative database, updated through institutional partnerships and public calls for project registration, will ensure that information remains current. Public-access interfaces will coexist with restricted areas offering advanced functions such as consortium creation, customized reporting, and joint calls for proposals.

Governance will be shared by a Brazil–Portugal consortium comprising technical, academic, and institutional representatives who will meet regularly to evaluate the platform, define categorization criteria, and validate information. To maintain relevance and dynamism, the observatory will incorporate mechanisms for continuous updating, including participatory workshops, hybrid forums (virtual and in-person), public consultations, and technical–scientific committees. Adherence to the principles of open science, transparency, and network governance will be central to fostering trust among stakeholders and ensuring the value of knowledge generated in local and regional contexts. This collaborative model follows the recommendations of the OECD (2023) and successful experiences such as the European Energy Research Alliance (EERA) and the Energy Innovation Observatory (EIO), both of which focus on territorial intelligence and green innovation.

To evaluate the initiative over time, a set of performance and impact indicators will be established. These will include the number of projects mapped, institutional partnerships formed, volume of data accessed, startups and spin-offs identified, active bilateral initiatives between Brazil and Portugal, and estimated CO_2-emission reductions associated with the technologies observed. Continuous measurement of these indicators will guide strategic adjustments and provide evidence for public policymakers and investors committed to supporting a just and sustainable energy transition.

Overall, the proposed International Observatory for Innovation in Low-Carbon Energy represents a strategic and high-impact initiative capable of connecting science, policy, and society through a modern and inclusive institutional architecture. By enhancing institutional maturity in energy innovation and promoting the internationalization of sustainable solutions, the observatory will foster networked governance and democratize access to critical knowledge, strengthening the global movement toward a low-carbon future.

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Comparison with Existing International Observatories

The proposal for an International Observatory for Innovation in Low-Carbon Energy linking Brazil and Portugal draws inspiration from established global models while addressing a specific gap in the Ibero-American context. Examining these precedents helps identify best practices and critical design elements for the new platform. Below are key international experiences that inform the conceptual and operational framework of this initiative.

European Energy Research Alliance (EERA) -The EERA is one of Europe's largest collaborative energy-research networks, bringing together over 250 research organizations across 30 countries. Its focus is to accelerate low-carbon technologies through joint programs, shared infrastructure, and open-data platforms. EERA demonstrates the value of coordinated governance across national boundaries, enabling rapid scaling of clean-energy innovations and providing a benchmark for structuring transnational partnerships.

Energy Innovation Observatory (EIO) – European Commission-The EIO, supported by the European Commission, serves as a data-driven observatory tracking trends in renewable energy technologies, investment flows, and innovation metrics. Its strengths lie in the systematic use of indicators, including Technology Readiness Levels (TRLs) and funding-source mapping, which directly informs EU policy decisions. The EIO illustrates how real-time, evidence-based analytics can guide strategic planning for decarbonization and aligns closely with the methodological pillars proposed for the Brazil–Portugal observatory.

International Renewable Energy Agency (IRENA) Knowledge Platform -IRENA's platform aggregates global renewable energy statistics, policy databases, and technology briefs, fostering information exchange among member states, industry, and civil society. Its success highlights the importance of open access to reliable data and capacity-building tools—features that the new observatory seeks to replicate to enhance stakeholder engagement in the Ibero-American region.

Latin American and Caribbean Energy Information System (SIELAC)- Managed by OLADE, SIELAC provides a regional database of energy statistics and policy documents for Latin America and the Caribbean. While valuable, it remains primarily statistical and less focused on innovation ecosystems or startup mapping, underscoring the unique contribution of a Brazil–Portugal initiative aimed at integrating research institutions, investors, and community actors into a single innovation-driven platform.

These international models converge on several success factors relevant to the proposed observatory:

Network Governance – as seen in EERA, effective cross-border cooperation relies on a balanced, multistakeholder governance structure.

Data Transparency and Standardization – demonstrated by EIO and IRENA, which use harmonized metrics (such as TRL levels) to compare technologies and projects.

Open Science and Stakeholder Engagement – evident in IRENA's open-access approach and community-building tools, ensuring that governments, industry, and civil society can all contribute and benefit.

By combining these best practices with a Quadruple Helix perspective integrating academia, government, industry, and civil Society the Brazil–Portugal observatory aims to fill a critical regional gap. It will not only map startups, spin-offs, and strategic investments but also foster transnational collaboration tailored to the energy-transition priorities of Ibero-America. Table 1 compares leading international energy observatories to position the proposed Brazil–Portugal initiative within the global landscape. While platforms such as the IEA Hydrogen TCP focus on government-led technical cooperation, the Energy Innovation Observatory (EIO) emphasizes European policy analysis, GO-P2P prioritizes community-based peer-to-peer models, and OLADE concentrates on regional energy statistics. In contrast, the proposed International Observatory for Innovation in Low-Carbon Energy integrates open innovation, Quadruple-Helix collaboration, and South–North Ibero-American cooperation, addressing a critical gap by combining technology mapping, startup tracking, and multisector governance to support evidence-based energy transition strategies.

Table 1 – Comparison of Existing International Energy Observatories

Observatory / Institution	Country / Region	Main Focus	Key Features	Limitations
IEA Hydrogen TCP – International Energy Agency	Multinational (OECD)	Technical cooperation and R&D in low-carbon hydrogen	Government-led expert network; joint technical projects and standardization initiatives	Limited engagement with startups and civil society
Energy Innovation Observatory (EIO) – Uppsala University	Sweden / Europe	Analysis of public policies and energy-innovation trends	Academic and regulatory focus; strong open-data infrastructure	Restricted to the European context and primarily governmental/institutional scope
GO-P2P – Global Observatory on Peer-to-Peer Energy Models (UCL)	United Kingdom	Decentralized energy models and energy justice	Emphasis on community participation and distributed energy transactions	Narrow focus on local consumption and peer-to-peer energy trading

OLADE – Latin American Energy Observatory (UNASUR)	Ecuador / Latin America	Regional energy planning and sector statistics	Technical data collection from 27 member countries; long-term regional datasets	Limited linkage with technological innovation; centralized statistical orientation
Proposed International Observatory for Innovation in Low-Carbon Energy	Brazil–Portugal / Ibero-America	Technological innovation in hydrogen, CCUS, and clean energy	Interactive platform; binational cooperation; open data; TRL metrics; active civil-society engagement; network governance	Strategic differentiator: combines open innovation, Quadruple-Helix integration, and South–North Ibero-American cooperation

Source: Prepared by the author

This comparison highlights how the Brazil–Portugal proposal fills a distinct gap in the current landscape. Unlike existing observatories that focus narrowly on either statistics, policy analysis, or specific technologies, the proposed platform integrates technology mapping, startup and spin-off tracking, funding sources, and cross-sector governance under a Quadruple-Helix model. By coupling South–North collaboration with Ibero-American outreach, it offers an innovative framework capable of strengthening clean-energy ecosystems while promoting open science and inclusive participation across academia, industry, government, and civil society.

4. Expected Results and Contributions

The proposed International Observatory for Innovation in Low-Carbon Energy is designed to generate measurable academic and practical impacts that will strengthen the Ibero-American ecosystem of science, technology, and innovation dedicated to a sustainable energy transition. Its expected results can be summarized in four major areas of impact.

First, the observatory will consolidate a strategic knowledge base on energy innovation across the Ibero-American region. Today, decision-making is hindered by the absence of integrated platforms capable of organizing, georeferencing, and analyzing projects, technologies, stakeholders, and funding sources. By aggregating data from multiple institutions, the observatory will create collective intelligence, helping identify gaps, opportunities, and synergies between countries.

Second, the initiative will provide direct support for public policy and market strategies in clean energy. Governments, funding agencies, and private investors will have access to systematic information on technology readiness levels (TRLs), commercial viability, social acceptance, and environmental impacts of ongoing projects. This evidence-based infrastructure will enable more effective financing mechanisms and targeted innovation policies with high social and environmental returns.

Third, the platform will reinforce international cooperation, especially between Brazilian and Portuguese institutions. By operating as a collaborative digital interface, the observatory will encourage transnational research consortia, attract international funding, and help create joint innovation agendas, thereby strengthening scientific and technological diplomacy and expanding the global reach of universities, research centers, and startups.

Fourth, the initiative will promote a more inclusive and participatory energy transition, recognizing civil society as a co-producer of knowledge. Open data, interactive forums, and the inclusion of social and territorial indicators in project analyses will foster democratic and transparent governance, attentive to regional inequalities.

Collectively, these outcomes underscore the observatory's role as an instrument of institutional and technological innovation, capable of catalyzing systemic change in energy production and use across Ibero-America.

Final Considerations

The creation of an International Observatory for Innovation in Low-Carbon Energy between Brazil and Portugal represents a strategic response to the demand for collaborative, data-driven models to guide the energy transition. Throughout this article, we demonstrated the relevance of a systemic innovation approach rooted in the Quadruple Helix model, which recognizes the interdependence of universities, industry, government, and civil society in co-producing solutions to global socio-environmental challenges. This perspective expands the traditional boundaries of technological innovation, placing clean energy at the heart of institutional, economic, and cultural transformation in the twenty-first century.

Among the study's main practical contributions is the design of a functional structure for the observatory capable of consolidating a strategic data base, promoting international cooperation, and connecting diverse stakeholders through an interactive digital platform. The proposal offers concrete tools to inform public policies, support business decisions, and foster open innovation—particularly in green hydrogen, electrification, and carbon capture and utilization (CCUS). It also reinforces the importance of network governance and transparency as structural principles for a low-carbon economy aligned with the Paris Agreement and the UN 2030 Agenda.Nevertheless, the implementation of such an observatory faces challenges. These include the heterogeneity of national innovation systems, unequal availability of open data, legal barriers to information sharing, and occasional institutional resistance to participatory innovation. Overcoming these obstacles will require political commitment, sustained investment, and the strengthening of technical and collaborative capacities among the countries involved.

This research opens avenues for future studies on the technical, legal, and financial feasibility of the proposed platform, as well as empirical investigations into the impact of similar observatories in other strategic areas of the green transition—such as regenerative agriculture, circular economy, and sustainable mobility. International comparative studies and the development of impact indicators are also recommended to evaluate the observatory's effectiveness in driving sustainable, socially legitimate innovation.In conclusion, although still at an initial stage, the proposal outlined here offers a promising pathway to bridge science, society, and policy, supporting a just, collaborative, and knowledge-based energy transition across the Ibero-American region.

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ENERGY EFFICIENCY IN PUBLIC EDUCATIONAL INSTITUTIONS: A CASE STUDY ON THE IMPLEMENTATION OF A PHOTOVOLTAIC SYSTEM AT CEFET-RJ

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ABSTRACT

This article presents a case study on the energy efficiency project to be implemented at the Federal Center for Technological Education Celso Suckow da Fonseca (CEFET-RJ), as part of ANEEL's Energy Efficiency Program in partnership with the utility company Light. The project involved the installation of a photovoltaic power plant with a capacity of 435.6 kWp, the modernization of lighting systems, and the implementation of educational and environmental initiatives. Although the plant has already been installed, it is awaiting commissioning by the utility company before being connected to the distribution grid, which currently prevents the collection of empirical data on actual energy consumption reduction. Therefore, this article focuses on outlining the project, its goals, and methodologies, providing a reference framework for future studies. The methodology was based on documentary and descriptive analysis, supported by the project's official reports. The results present the planned technical, budgetary, and sustainability parameters. The discussion highlights the initiative's potential positive impact and the preliminary lessons that support the promotion of new energy efficiency projects in educational institutions. The conclusion emphasizes the importance of integrating infrastructure, education, and energy efficiency in public institutions.

KEYWORDS: Energy Efficiency Program; Photovoltaic Solar Energy; Educational Institutions; Sustainability; Case Study.

1 INTRODUCTION

Energy efficiency has been gaining prominence in the global political and economic landscape as a key strategy for sustainable development. Public institutions, such as administrative and educational buildings, play a significant role in this process, both due to their energy consumption capacity and their potential to disseminate knowledge and raise awareness. Bill No. 3907 of 2021 reinforces the importance of sustainable development by proposing the mandatory installation of photovoltaic energy systems in buildings used by direct and indirect federal public administration agencies and entities (Federal Senate, 2022). In this context, ANEEL's Energy Efficiency Program (PEE), in partnership with electricity distribution companies, has promoted projects focused on optimizing energy consumption across various sectors, including the provision of non-repayable funding (ANEEL, 2025). The agency has already enabled the implementation of approximately 4,800 projects through Brazilian utility companies, with an investment totaling around BRL 7.87 billion over the past 22 years. ANEEL highlights the potential for more investments in projects to reduce electricity consumption, supporting a fair and sustainable energy transition.

Fig. 1. Current energy benefit**.** Source: ANEEL, 2015.

ANEEL's PEE Observatory provides visualization of indicators related to the use of public funds from the program. As shown in Graph 1, in the years 2014, 2015, and 2016, the investment values reached significant peaks between BRL 45 and 55 million per year. However, starting in 2017, these values returned to levels similar to those of 2009, which may indicate a reduction in funding or project execution during the 2017–2020 period. Given the relevance of the topic and the funding offered by ANEEL's Energy Efficiency Program (PEE), this article analyzes the project to be implemented through the Program at the Maracanã campus of CEFET-RJ. The project includes the installation of a photovoltaic solar power plant, the replacement of lighting systems, and awareness-raising actions for the efficient use of energy. Since the power plant has not yet been connected to the utility company's grid, this study is limited to outlining and analyzing the project's goals, technical data, and estimated impacts. The aim is to provide a technical report that can support future quantitative evaluations and help encourage the implementation of new energy efficiency projects in educational institutions.

2 LITERATURE REVIEW

The literature review was organized into four thematic axes that are directly aligned with the objectives and scope of the present study: (1) Energy Efficiency in Public Buildings; (2) Photovoltaic Systems in Educational Institutions; (3) Public Policies and Regulatory Programs in the Electric Sector; and (4) Environmental Education and Energy Awareness.

2.1 Energy Efficiency in Public Buildings

Energy efficiency in public buildings has been the focus of policies and studies around the world, with an emphasis on reducing operational costs and carbon emissions. According to Rupp et al. (2021), interventions such as lighting retrofits, modernization of HVAC systems, and building automation have a high potential for impact when applied on a large scale in public buildings.

Barros et al. (2022) note that prioritizing public buildings is strategic, given their multiplier role. Energy use should be an institutional guideline, linking operations with management and education.

2.2 Photovoltaic Systems in Educational Institutions

The adoption of photovoltaic (PV) systems has been growing in universities and technical schools as part of institutional sustainability policies. According to Costa et al. (2023), the use of distributed generation on educational campuses reduces costs, improves environmental performance, and offers pedagogical opportunities in technical and engineering programs.

Case studies such as that of Lima et al. (2021), which analyzed the implementation of a PV system at a federal university, indicate that the challenges go beyond installation: they involve regulatory issues as well as the need for internal training for operation and maintenance.

2.3 Public Policies and Regulatory Programs in the Eletric Sector

The Energy Efficiency Program (PEE), regulated by ANEEL since 2000, is a key instrument for promoting efficiency in Brazil’s electricity sector. Santos and Almeida (2022) highlight that projects in public institutions deliver the highest social return, especially when linked to renewable generation.

ANEEL requires dissemination of the program’s logo and training for those involved, to ensure visibility and awareness (PROPEE-ANEEL, 2021).

Despite its reach, bureaucracy and disbursement schedules limit its potential. Andrade and Gonçalves (2023) recommend simplifying processes and regionalizing project calls to improve results.

2.4 Environmental Education and Energy Awareness

The literature also emphasizes the importance of educational and engagement initiatives as part of energy efficiency projects. According to Souza and Figueiredo (2021), awareness programs promote lasting behavioral changes, amplifying the effects of the implemented technological actions. Initiatives in technical schools and universities may range from informational campaigns to the curricular integration of sustainability topics, which strengthens users’ sense of belonging and responsibility.

Programs like Ecoenel, which is also maintained by the utility company using funds from the Energy Efficiency Program (PEE), are innovative and educational. The program’s proposal is to convert recyclable waste into direct discounts on electricity bills. By participating, consumers contribute to the environment, ensure the environmentally proper disposal of their waste, and receive a discount on their energy bill (Enel, 2025).

3 METHODOLOGY

This research adopts a descriptive case study approach, with an exploratory and documentary character. Primary sources from the project proposal were used, including sections such as the work plan, energy diagnosis, physical and financial schedules, technical reports, and supply scopes. This documentation is public and made available by ANEEL's Energy Efficiency Program (PEE) Observatory through Light Distribuidora de Energia S.A., and it refers to the implementation of the energy efficiency project at CEFET-RJ, Maracanã campus.

The method is based on a qualitative and quantitative analysis of the technical and operational data presented in the project, focusing on the stages of energy diagnosis, planning, and execution plan. Since the photovoltaic plant is not yet connected to the power grid, it was not possible to carry out empirical measurements to analyze the post-implementation energy impact. Therefore, the research is limited to collecting technical parameters, projected goals, and estimated savings based on the assumptions adopted by the project's engineering team.

However, it is worth addressing the project public call (CPP) issued by Light using funds from ANEEL's Energy Efficiency Program (PEE), through which CEFET-RJ was awarded funding for project execution. The CPP makes project selection more transparent. Each utility must conduct at least one CPP per year to gather new projects for PEE-ANEEL funding (PROPEE-ANEEL, 2021). It was through Light's 5th CPP that CEFET was selected to carry out the EE project.


ANEEL Agência Nacional de Energia Elétrica
PEE - Programa de Eficiência Energética
Light

RESULTADO - 5 ª CHAMADA PÚBLICA DE PROJETOS PEE LIGHT Nº 002/2018

Projeto Aprovado - Nota: 70,59

Proponente:	ENEL X
CNPJ:	08.317.250/0001-61
Projeto:	CEFET - Unidade Maracanã
Tipologia:	Poder Público
Cliente:	CEFET - Unidade Maracanã
CNPJ:	42.441.758/0001-05
Recursos R$	
Programa de Eficiência Energética (PEE):	2.608.931,33
Contrapartida:	2.600,00
Valor Total:	2.611.531,33
Dados do Projeto	
Relação Custo Benefício (RCB):	0,48
Usos Finais:	IL / FI
Energia Economizada (E.E.) MWh/ano	1.143,31
Redução de Demanda na Ponta (RDP) kW	135,73

Legenda
IL – Iluminação
CA – Condicionamento Ambiental
FI – Fontes Incentivadas
SM – Sistemas Motrizes
AS – Aquecimento Solar
OU – Outros Usos

Fig. 4. Result of the 5th Public Call for Projects (CPP). Source:Light, 2018.

To develop the project and compete in Light's Public Call for Projects (CPP), the following data and documents were systematized:

- Characteristics of the building and its electricity consumption profile;
- Technical descriptions of the photovoltaic plant (number of modules, inverters, occupied area, installed capacity);
- Budget spreadsheets and physical-financial schedule;
- Equipment disposal plans and planned educational actions;
- Estimates of energy and financial savings, and peak demand reduction;
- Calculation methodology based on measurement and verification protocols (IPMVP);
- Cost-benefit ratio (CBR) lower than 1;
- Cost of Saved Energy (CSE) and Cost of Demand Reduction (CDR).

The project's scope includes improving the energy efficiency of the lighting system in the consumer unit and implementing a photovoltaic solar system.
Through this project, obsolete technologies will be replaced with efficient, high-performance technologies. Additionally, by raising awareness among users about the safe and efficient use of electricity, the project aims to achieve energy savings and reduce peak demand. In this context, the project presents the main points of optimization of the existing systems in the facility by comparing them with the proposed systems. Based on this comparison, the benefits were estimated and confronted with annualized costs to assess the technical and economic feasibility of the project's implementation.

4 RESULTS

The project to be implemented at CEFET-RJ, Maracanã campus, involves several coordinated and integrated stages aimed at achieving significant improvements in energy efficiency. The main components of the project, as well as the projected outcomes, are detailed below.

4.1 Campus Unit Description

The Maracanã Campus of the Centro Federal de Educação Tecnológica Celso Suckow da Fonseca (CEFET/RJ) is one of Brazil's leading references in technological education. Its history began in 1917 with the founding of the Escola Normal de Artes e Ofícios, created to provide technical and vocational training in the context of early industrialization. Over the decades, the institution evolved into the National Technical School, gaining national prominence, and in 1978 it was transformed into a Federal Center for Technological Education, adopting the name that honors Celso Suckow da Fonseca (CEFET-RJ, 2021; Brazil, 1978).
Today, the Maracanã Campus is the administrative headquarters and reflects CEFET/RJ's mission of integrating teaching, research, and extension activities. The site covers 34,382 m² of land and 64,818 m² of total built floor area, distributed across eleven blocks and six pavilions. Its structure includes 72 classrooms, 166 laboratories and workshops, nine auditoriums, a central library, video libraries, and a sports complex with gymnasium, swimming pool, and athletic track.
In addition to academic spaces, the campus also has administrative areas and services that support students, staff, and faculty, as well as a teaching resource center dedicated to innovation and pedagogical development. This infrastructure underpins the institution's role in training professionals committed to Brazil's scientific, technological, and social advancement.

4.2 Consumer Unit Characterization

The consumer unit CEFET-RJ – Maracanã campus has an average annual electricity consumption of 1,152 MWh. In addition, the institution faces typical challenges of older buildings, such as inefficient lighting systems and the absence of real-time energy monitoring.

MÊS (mês/ano)	Consumo ponta	Consumo fora ponta	Demanda ponta	Demanda fora ponta	Consumo total
	kWh/mês	kWh/mês	kW	kW	kWh/mês
jul/22	15.624	134	750	820	149.915
ago/22	13.484	120.229	750	820	133.713
set/22	10.626	92.560	750	820	103.186
out/22	17.476	142.052	750	911	159.528
nov/22	16.250	135.853	750	822	152.103

dez/22	15.989	140.162	750	820	156.151
jan/23	15.718	133.862	750	857	149.580
fev/23	9.093	104.404	750	933	113.497
mar/23	29.366	210.883	750	933	240.249
abr/23	19.054	146.815	750	820	165.869
mai/23	16.479	85.453	750	820	101.932
jun/23	14.478	112.972	750	820	127.450
jul/23	9.100	87.394	750	820	96.494
ago/23	17.683	123.833	750	826	141.516
set/23	21.336	170.024	750	1.034	191.360
out/23	21.092	151.931	750	820	173.023
nov/23	20.909	170.881	750	1.039	191.790
dez/23	14.598	144.295	750	906	158.893
jan/24	10.401	119.372	750	820	129.773
fev/24	16.517	153.972	750	987	170.489
mar/24	26.253	195.123	809	1.059	221.376
abr/24	23.941	176.223	750	862	200.164
mai/24	12.054	125.017	750	820	137.071
jun/24	8.019	89.006	750	820	97.025
MÉDIA	16.480,83	136.108,63	752,46	875,38	152.589,46
TOTAL (12 meses)	395.540,00	3.266.607,00	-	-	3.662.147,00

Table 1. Unit Overall Consumption. Source: Prepared by the authors, adapted from CEFET, 2024.

The energy input used in the facilities is electricity supplied by the utility company, with the unit being powered by a medium-voltage substation, sub-group A4.
Figure 6 presents a chart with the estimated share of each of the end uses observed in the current facilities of CEFET/RJ.

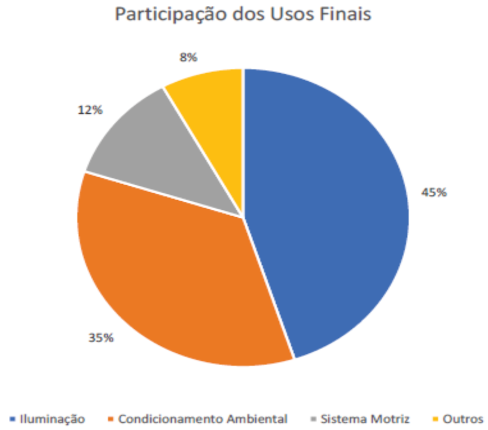

Fig. 6. Estimated Share of Each System in CEFET/RJ's Final Energy Consumption. Source: DEODE, 2023.

It is observed that lighting and air conditioning account for 80% of the unit's total electricity consumption. This fact is a key point in the project, which also includes the replacement of inefficient lamps with high-efficiency lighting, in addition to the installation of the solar power plant.

4.3 Photovoltaic Generation

The installation of a solar plant with a capacity of 435.6 kWp is planned, consisting of 660 modules of 660 Wp each and a lifespan of 20 years, to be installed on 2,349 m² of the roof of Block A. The projected annual generation is approximately 659 MWh (DEODE, 2023). The energy will be injected directly into the campus's main low-voltage distribution panel, in compliance with the local utility's regulations. The system will be remotely monitored through a supervision platform, allowing for performance tracking and fault detection.

Fig. 7. Plant Installation Site. Source: DEODE, 2023.

The installation of the photovoltaic system will take place within the premises of the consumer unit, with the mounting structure for the panels making use of the existing roof slope. No civil works, structural reinforcement, or anti-corrosion treatment will be required.

4.4 Lighting System

Considering that the lighting system accounts for 45% of CEFET/RJ's total energy consumption, the replacement of 1,393 lighting points is planned. Inefficient lamps—including mixed, sodium vapor, incandescent, and metal halide lamps—will be replaced with high-efficiency LED luminaires. This action is expected to generate estimated savings of 257.68 MWh/year, in addition to a reduction in peak demand of 58.83 kW (DEODE, 2023). The project covers various types of spaces, including classrooms, laboratories, corridors, and administrative areas. Upon implementation, the lighting levels will be adjusted in accordance with ABNT standards to ensure visual comfort and safety.

Fig.8. Outdoor Lighting Example. Source: CEFET, 2024.

At the end of the action to replace inefficient lamps with LED luminaires, an annual savings of BRL 169,495.37 is expected for CEFET/RJ.

4.5 Educational and Environmental Actions

The awareness actions include workshops on the rational use of energy, technical training for staff on the operation of the power plant, distribution of informational materials, and institutional campaigns. This action is mandatory to comply with ANEEL regulations, as the project will be funded by resources from the PEE-ANEEL (PROPEE-ANEEL, 2021). The planned actions are listed below. This initiative is essential alongside the efforts to improve the lighting system and implement the photovoltaic solar system, and it will be carried out to ensure that energy resources are used consciously.

The rational energy use training will primarily cover the following topics:

- Replacing halogen and fluorescent lamps with LED lamps. The initial cost will be offset by energy savings;
- Turning off lights that are not in use, except those that contribute to safety;
- Painting walls and ceilings with light colors. In addition to reflecting natural light better, this reduces the need for artificial lighting;
- Avoiding the use of artificial lighting during the day—opening windows and maximizing the use of natural light;
- Guidance on the use of equipment bearing the PROCEL SEAL.

In addition to the rational energy use workshop, several training sessions will also be held for staff, especially the maintenance team, regarding the operation of the newly installed equipment, maintenance procedures, and how the equipment warranty process will work, along with the delivery of the project warranty manual. Upon project completion, a manual will be delivered to the beneficiary containing all information about the installed equipment, technical contacts, project warranties, and instructions on how to proceed in the event of potential incidents (DEODE, 2023).
These actions aim to promote users' shared responsibility and enhance the benefits obtained through technological interventions. Additionally, a proper environmental disposal plan for the replaced equipment will be implemented. Environmentally appropriate disposal is a mandatory step to comply with ANEEL regulations for projects funded by PEE-ANEEL resources (PROPEE-ANEEL, 2021).

4.6 Budget and Feasibility Analysis

The project aims to improve the energy efficiency of the lighting system and to install an incentivized energy source at the CEFET/RJ unit, Maracanã campus. The referenced project proposal sets targets of 916.68 MWh/year in energy savings and a peak demand reduction of 58.83 kW. For the implementation of the project, a PEE-ANEEL cost of BRL 2,239,568.24 was accounted for, with a Cost-Benefit Ratio (CBR) of 0.40. These indicators exceed ANEEL's minimum threshold values, characterizing the project as technically and economically feasible (DEODE, 2023). Thus, the actions are shown to be technically and economically attractive for the consumer unit benefiting from the project.

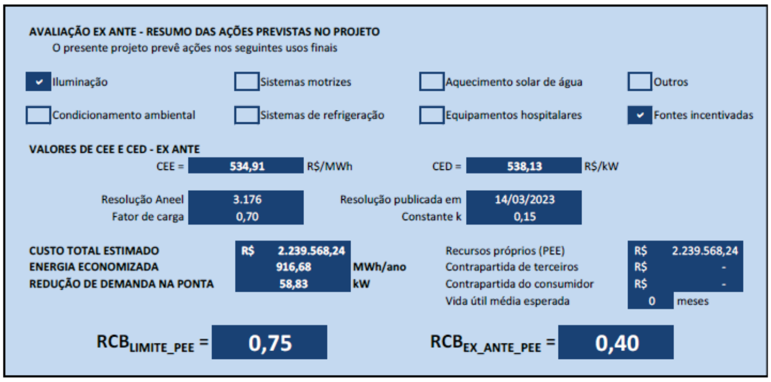

Fig. 11. Summary of the Expected Results after Implementation of the Project with PEE-ANEEL Funds. Source: PEE-ANEEL, 2024.

After the implementation of the energy efficiency actions, CEFET/RJ is expected to achieve annual savings of BRL 450,367.19, demonstrating that the project is effective and that, through PEE-ANEEL, it is possible to carry out efficient actions that benefit not only the unit receiving the project but society as a whole.

5 DISCUSSION

The technical and budgetary assessment indicates a promising energy efficiency solution for the public education sector. The intervention model adopted—based on the integration of distributed generation technologies, lighting system retrofit actions, and training and capacity-building initiatives—follows the most recent recommendations from the specialized literature. The photovoltaic generation component, although not yet operational, represents a key element not only due to its expected economic return but also for its symbolic and educational impact. The visible presence of the solar plant and its incorporation into academic subjects and institutional activities may foster an institutional culture of sustainability, aligning with the goals of the 2030 Agenda.

From a technical standpoint, replacing the outdated lighting system with LED technology constitutes a high-impact intervention, offering a relatively short payback period and immediate effects on energy consumption. The selection of certified equipment and compliance with lighting standards ensure not only efficiency but also safety and comfort in the educational environments used by the many students at the Maracanã campus.

A noteworthy aspect is the systemic approach adopted, which includes the project's conception, as well as the planning of operational, maintenance, and continuous engagement actions. This distinguishes the project from isolated interventions and ensures its sustainability in the medium and long term.

Nevertheless, it is important to acknowledge the limitations. The most significant is the lack of real performance data from the photovoltaic plant to date, which prevents empirical validation of the estimated gains. In addition, potential delays in grid connection may compromise the effectiveness of the strategy, especially regarding return on investment.

Finally, it is worth highlighting that the experience gained through this project may serve as a reference for other public institutions, especially those facing similar challenges related to outdated infrastructure and limited budgets. It is important to note that the funds used for project execution were 100% provided through PEE-ANEEL, ensuring that the resources were allocated as non-repayable funding. Therefore, replicating the model will depend solely on the institutional mobilization capacity of educational institutions, requiring coordination and engagement from the school community to submit an application for one of the CPPs held by the local energy utility.

6 CONCLUSION

The integration of a photovoltaic plant, lighting modernization, and educational initiatives represents a comprehensive strategy aligned with the UN's 2030 Agenda and the goals of Brazil's energy transition. Together, these actions are expected to generate significant outcomes, including annual electricity savings projected at more than 900 MWh — the equivalent of supplying dozens of homes for a year — and a peak demand reduction of nearly 60 kW. These improvements translate into estimated financial savings of over BRL 450,000 per year for CEFET-RJ, resources that can be reinvested into education, research, and infrastructure.

The project was fully funded by PEE-ANEEL resources (BRL 2.24 million), proving that non-repayable public investments can produce substantial technical, economic, and environmental returns. In addition to the direct financial gains, the initiative strengthens the institution's role as a reference for sustainable practices in the public education sector by combining infrastructure upgrades with awareness campaigns that involve students, teachers, and staff.

Once the photovoltaic system is fully commissioned, it will be crucial to monitor real operational data to confirm the projected impacts and adjust strategies where needed. This monitoring will also expand the knowledge base on energy efficiency in educational environments, paving the way for new studies and improvements. Based on this real-world performance, a follow-up study can be developed to validate assumptions, refine projections, and document the long-term impacts of the project. The experience at CEFET-RJ shows how public institutions can mobilize around CPP calls, access funding, and replicate a model that integrates technology, education, and energy governance to deliver tangible benefits — reducing costs, cutting emissions, and advancing Brazil's sustainability goals.

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LITERATURE REVIEW ON PUBLIC POLICIES APPLIED TO PHOTOVOLTAIC MODULES CONSIDERING THE CIRCULAR ECONOMY

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ABSTRACT

The exponential growth of solar photovoltaic (PV) energy systems is driving the urgent need for effective public policies for managing modules at the end of their useful life (EoL). This article aims to analyze, from a circular economy prespective, the regulatory approaches adopted by leading solar energy countries, identifying challenges, opportunities and best practices. The urgency of this discussion of the topic is heightened by the projected increase in photovoltaic waste over the coming decades, which requires strategic actions to prevent environmental impacts and promote the efficient use of resources. The analysis includes a review of the technological and market panorama of the solar sector as well as, alternatives for the reuse and recycling solar panels. Emerging technologies, such as advanced material separation processes and component reuse, are considered alongside with extended producer responsibility (EPR) as part of strategic waste management. The study highlights the need for adequate recycling infrastructure, the integration of environmental criteria into public policies and the promotion of sustainable innovation. Therefore, it is evidente that the formulation of policies based on technical data and successful international experiences is essential to ensure a sustainable and safe energy transition in line with the principles of the circular economy.

KEYWORDS: Public policies, circular economy, photovoltaic; end-of-life, literature review and solar panel.

1 INTRODUCTION

The growing urgency to mitigate climate change has encouraged the transition to renewable energy sources. Among these, photovoltaic solar energy has stood out due to its scalability, decreasing costs and global availability. By 2024, the world's installed renewable energy capacity is expected to exceed 4,440 GW, with solar energy accounting for more than 40% of this total. China leads this ranking with 888 GW, followed by the USA, India, Japan, Germany and Brazil (IRENA, 2025). Studies already show that by 2050 waste from solar photovoltaic plants could exceed 60 million tons globally (IRENA, 2016). With an average lifespan of 30 years and a complex composition of raw materials, the environmentally sound disposal of modules after decommissioning remains a challenge (K. M. D. Nimesha, et al., 2024). The disposal process needs to be economically viable, which is still hindered by the lack of global public policies and limited investment aimed at reducing the costs in the procedures of implementing methodologies aligned the principles of the 3 R's policy: reduce, reuse and recycle (Piramidal, 2020 and A. Rubino et al., 2020). Although China, the USA, India, Japan, Germany and Brazil are the countries with the largest installed solar energy capacity, and consequently the largest generators of photovoltaic waste, they still lack specific global regulations for this type of material, which is often classified as generais, electrical and electronic, or industrial waste (IRENA, 2016). This scenario shows that the existing infrastructure remains insufficient to manage the growing volume of waste generated by the solar industry (Ali et al., 2024).

For this reason, this research proposes a critical evaluation of the strategies applied to the end-of-life (EoL) management of photovoltaic panels (PVs), presenting an overview of the regulatory public policies in force in different countries. The study also analyzes the evolution of these policies over the years, considering both regulatory developments and technological advances in recycling processes. Furthermore, it introduces a promising approach to adress this issue, emphasizing the importance of adopting the circular economy (CE) model as a key strategy to mitigate the environmental impacts associated with the improper disposal of solar modules.

2 OVERVIEW BY SOLAR PHOTOVOLTAIC TECHNOLOGY

The categorization of the most common photovoltaic module technologies reflects their evolution over the years: the first generation modules consist of monocrystalline and polycrystalline silicon (c-Si); secondgenerationmodules are based on thin films, such as cadmium telluride - CdTe and copper-indium-gallium-selenium alloy - CIGS); and thirdgeneration modules comprise emerging Technologies, including perovskites, concentrated photovoltaics (PCV), III-V alloys and others (G. Regmi et al., 2020; R. A. Regmi et al., 2022), 2020; R. A. Marques et al., 2022). The efficiency of photovoltaic modules varies depending on the technology used, directly influencing the commercial viability and applicability of each type. Each generation is explained in this section.

2.1 Efficiency of different solar cell technologies

The first generation, composed of crystalline silicon (c-Si), represents the most mature and widespread photovoltaic technology, as previously mentioned. Monocrystalline modules (mono-Si) offer higher efficiencies, typically ranging from 15% to 22% (G. Regmi et al., 2020), and can reach up to 26.1% under ideal conditions (R. A. Marques et al., 2022). They are more expensive due to the more refined manufacturing process. In contrast, polycrystalline cell modules (poly-Si) exhibit lower efficiencies, generally between 13% and 18%, although they are a more affordable alternative. It is worth noting that, since their development, crystalline silicon photovoltaic cells have increased in efficiency by 20.1 percentage points, from 6% to the current record of 26.1% (R. A. Marques et al., 2022). The evolution of technology and improvements in manufacturing processes have been fundamental to this advance.

The second generation, thin films (CIGS and CdTe), stand out for being lighter, more flexible and economical, but historically they have lower efficiency than crystalline silicon modules. The CIGS type initially had low efficiency, but advances in research have raised this figure to 18-20% (M. G. Buonomenna, 2023). Therefore, this technology currently has competitive potential compared to c-Si, with the highest laboratory efficiency results being 23.6% for CIGS and 22.3% for CdTe solar cells (G. Regmi et al., 2020). This type is known for its high absorption and low energy loss, making it a viable alternative for high-temperature regions.

The third generation, composed of emerging technologies (perovskites, CPV, III-V alloys and others), aims to surpass previous generations by exploring new materials and photovoltaic cell architectures. Perovskite cells exhibit the fastest growth in efficiency, from 3.8% in 2009 to a current laboratory efficiency of 21% (R. A. Marques et al., 2022). CPVs, on the other hand, use lenses or mirrors to concentrate sunlight into high-efficiency photovoltaic cells, achieving efficiencies of over 40%. III-V alloys, composed of semiconductor materials such as GaAs (gallium arsenate), are mainly used in specialized applications and high-efficiency systems, with an average efficiency of 30% under concentrated light (G. Regmi et al., 2020).

Figure 1 - Categorization of photovoltaic panels, 1st, 2nd and 3rd generation, respectively.
Source: Portal Solar 2025 e Turano Construtora, 2021.

C-Si cells are the predominant technology on the market, recognized for their high reliability and consolidated performance. At the same time, thin film technologies such as CIGS and CdTe are emerging as competitive alternative, especially for specific applications that require flexibility and lower production costs (G. Regmi et al., 2020). Meanwhile, emerging technologies such as perovskite cells present revolutionary potential for the photovoltaic sector, combining high efficiency with more accessible manufacturing processes. However, challenges such as stability, durability and commercial viability still need to be overcome for this innovation to reach large-scale production (M. G. Buonomenna, 2023). Thus, the future of photovoltaic solar energy focuses on the continuous search for greater efficiency, cost reduction and lower environmental impact, driving new research and technological developments for more affordable and sustainable energy generation.

3 WASTE FROM THE SOLAR PHOTOVOLTAIC INDUSTRY

It is estimated that by 2050, PV waste could exceed 60 million tons globally (IRENA, 2016). To mitigate this future impact, end-of-life (EoL) waste management should be implemented in accordance with the principles of environmentally sound management, which include: prevention, reuse, recycling and safe disposal. For this reason, the main manufacturers of solar modules will be presented, along with recycling technologies that include mechanical, thermal and chemical processes, aiming to recover glass, silicon, aluminum and rare metals (IRENA, 2022).

3.1 Global ranking of solar panel manufacturers

The global ranking in installed solar photovoltaic capacity is led, respectively: by China, the United States, India, Japan, Germany, Brazil, Spain, Australia, Italy and South Korea. By 2024, these ten countries will have added a total of 1,537,167.00 GW of photovoltaic solar generation, with China leading by a wide margin and continuing to add significantly expand its renewable energy infrastructure, accounting for approximately 60% of global installations in 2024 (IRENA, 2025).

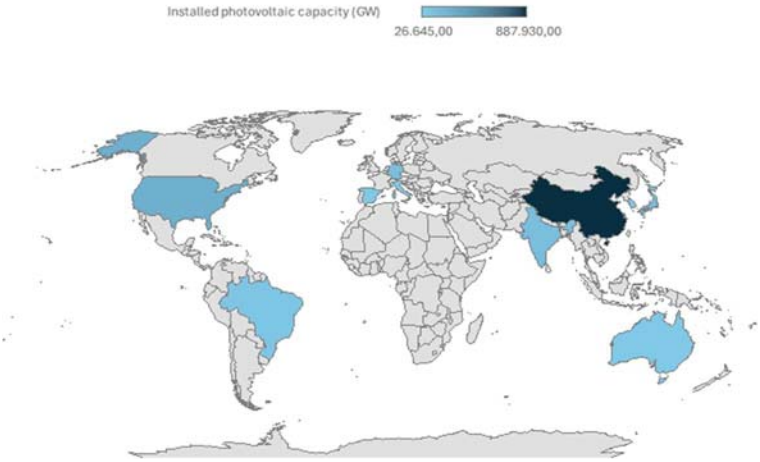
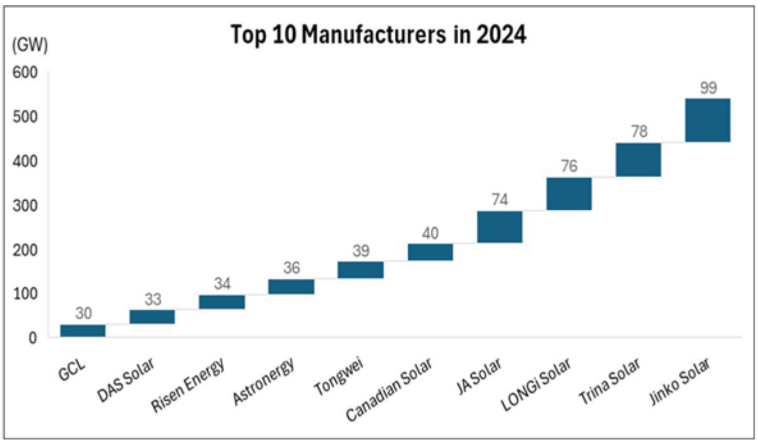


Figure 2 - Installed photovoltaic capacity (2024). Source: Original work by the author, 2025.

China's dominance in the photovoltaic sector goes beyond its installed power generation capacity. The country has also established itself as the world's leading manufacturer of solar modules. According to the global ranking of the ten largest manufacturers in 2024 (InfoLink, 2025), all the companies listed are based in China, demonstrating its consolidated leadership in the photovoltaic supply chain (Portal Solar, 2025).



Graph 1 - The top 10 manufacturers in 2024. Source: Original work by the author, 2025.

The four largest companies (JinkoSolar, LONGi Solar, Trina Solar and JA Solar), all based in China, have remained in the lead since 2019 (Clean Energy Portal, 2024). Part of this leadership is justified by financial incentives for producers, as China invests significantly in research and development (R&D) in the solar energy sector. In 2023, the Chinese government allocated US$676 billion to R&D, promoting technological advances that have strengthened China's position as a global leader in photovoltaic innovation (Nguyen, M.P. and Ponomarenko, T., 2025).

3.2 Technologies and practices for recycling and reusing photovoltaic modules

The growing global demand for clean energy, driven by decarbonization targets, has led to an increase in panel production, which grew by 22% from 2023 to 2024 (InfoLink, 2025). However, the volume of photovoltaic modules reaching the end of their useful life is also increasing, which is why a number of innovative technologies have been developed to maximize material recovery and enable the efficient reuse of components.

The first generation of modules (crystalline silicon) represents the largest share of the photovoltaic market. Recycling these modules involves steps such as dismantling, material separation, and the recovery of valuable components (Nguyen, M.P. and Ponomarenko, T., 2025). It is possible to recover glass and silicon, glass alone accounts for approximately 70% of the module's weight. Studies show that up to 90% of the silicon in panels can be recovered through techniques such as chemical and thermal treatments (Gopalamma et al., 2021). Recycling these panels helps reduce environmental impacts, including greenhouse gas emissions and heavy metal contamination. Studies also indicates that the efficient recovery of these materials is essential to minimizing the environmental risks associated with improper disposal (Kowalski, Z., et al., 2021).

For secondgeneration modules (CdTe and CIGS), First Solar stands out. The company has implemented a global recycling program that enablesthe recover up to 95% of semiconductor materials and 90% of the glass in CdTe modules. It is also the only US-based company ranked among the world's top 15 module producers in 2024 (InfoLink, 2025). Its treatment process involves grinding the modules, mechanically separating the glass and chemically removing the semiconductor layers, resulting in high-purity materials for reuse (First Solar, 2024). For CIGS modules, which also belong to the second generation, methods such as hydrometallurgy have been explored to recover valuable metals such as indium, gallium and selenium. Studies indicate that it is possible to achieve recovery rates of over 90% for these materials, contributing to sustainability and reducing environmental impacts (Xiang Li, et al., 2023).

The third generation (perovskites, CPV and III-V alloys), consists of emerging technologies that present unique challenges for recycling due to their innovative composition and structure. In perovskite panels, for example, the cells contain materials such as lead, requiring special care during recycling to avoid environmental contamination (Raphael, E., et al., 2018). CPV and Alloy III-V cells also use rare and valuable materials such as gallium and arsenic, so research is underway to develop efficient methods for recovering these materials, including chemical extraction processes and component reuse (Sah, D., et al., 2023).

It should be noted that recycling these modules is crucial not only to recovering valuable materials but also for reducing dependence on raw materials. Although photovoltaic technologies are categorized into three generations, the recycling process is mainly based on three stages. The researchers Liu et al. (2020), described in his study the processes typically observed in photovoltaic panel recycling systems at the end-of-life stage, divided into the following steps:

I. Collection stage; the solar plant is dismantled and the panels are purchased by recycling institutions;

II. Transport stage; consists of transporting the modules to a recycling center; and

III. Treatment stage; the recycler processes the materials, subdivided into mechanical, thermal and chemical treatment processes.

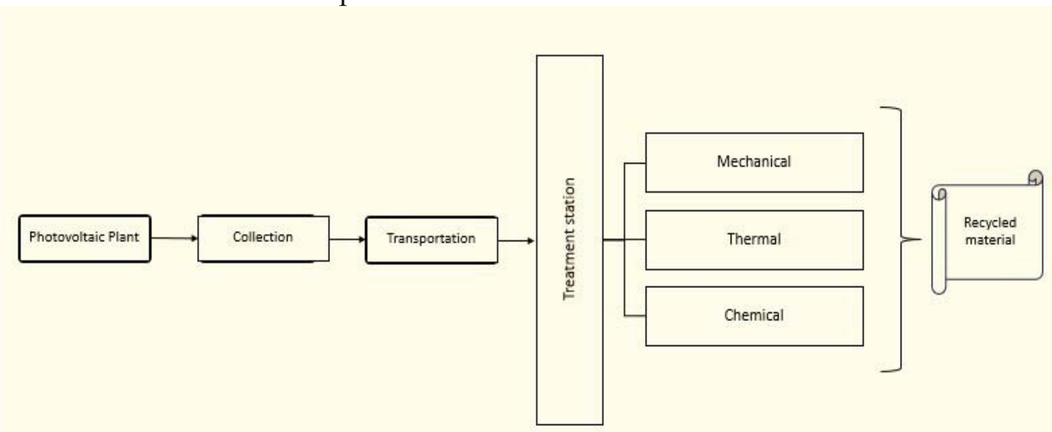


Figure 3 - Recycling system for photovoltaic panels. Source: Adapted from Liu *et al.,* 2020.

Despite advances in recent decades, the recycling of photovoltaic modules still faces significant obstacles, particularly regarding the economic viability and efficiency of the processes involved in recovering recycle materials (Chowdhury et al., 2020). Although c-Si modules have more estabilished recycling processes, second- and third generation technologies still require research to develop efficient and economically sustainable solutions (Celik et al., 2016). These challenges highlight the urgent need for public policies and incentives to promote large-scale recycling, as the recovery and reuse of materials are essential to ensuring a fair and sustainable energy transition in solar energy generation (Zhang, Y., et al., 2024).

Innovative approaches are emerging and the implementation of this strategy contributes to reducing environmental impacts. Therefore, applying the principles of the circular economy for photovoltaic technologies promotes the reuse and a reduction in the carbon footprint. Successful examples include ElecSome in Australia and First Solar in Ohio, Malaysia, Vietnam, Germany and India.

The innovative approach to reusing solar panels involves using recycled glass to produce cement and concrete. ElecSome (https://www.elecsome.com/), an Australian company, has developed SolarCrete, a pre-mixed concrete product that partially replaces natural sand with fine glass particles from decommissioned solar panels. Another emerging solution is the reuse of photovoltaic module components to manufacture new solar panels, which helps avoid the production of virgin materials. However, this reuse process requires the application of various treatments, including thermal, mechanical and chemical methods (A. Rubino et al., 2020).

First Solar also recognizes the importance of responsible product lifecycle management and has designed its panels for high-value recycling, maximizing the recovery of materials at the end of their useful life. The company recovers around 90% of reuse, providing high-quality secondary resources for new solar panels, as well as for other products such as glass, rubber and aluminum materials (First Solar, 2024).

However, both First Solar and PV CYCLE (https://pvcycle.org/), along with other companies, highlight challenges such as stricter public policies, the lack of recycling infrastructure and the currently low volume of end-of-life photovoltaic modules as obstacles to the development of the materials supply chain in solar energy generation (Silva et al., 2024).

4 RESULTS AND DISCUSSION

This highlights the importance of developing adequate infrastructure for managing photovoltaic waste, as well as the need to incorporate environmental criteria into public policies and promote innovation in the solar sector. The adoption of integrated policies, based on technical data and successful international experiences, can contribute to the development of effective regulatory models. These models must align with the principles of the circular economy and be adapted to the reality of each country, in order to enable the implementation of efficient recycling and disposal processes for solar panels, allowing solar energy to fulfill its role in a sustainable global energy transition.

4.1 Analysis of regulatory public policies for the EoL of PVs EoL

This section examines the current regulatory policies in each of the ten countries that comprise the global ranking for installed solar photovoltaic generation capacity. Figure 4 summarizes the existing legislation in these countries.

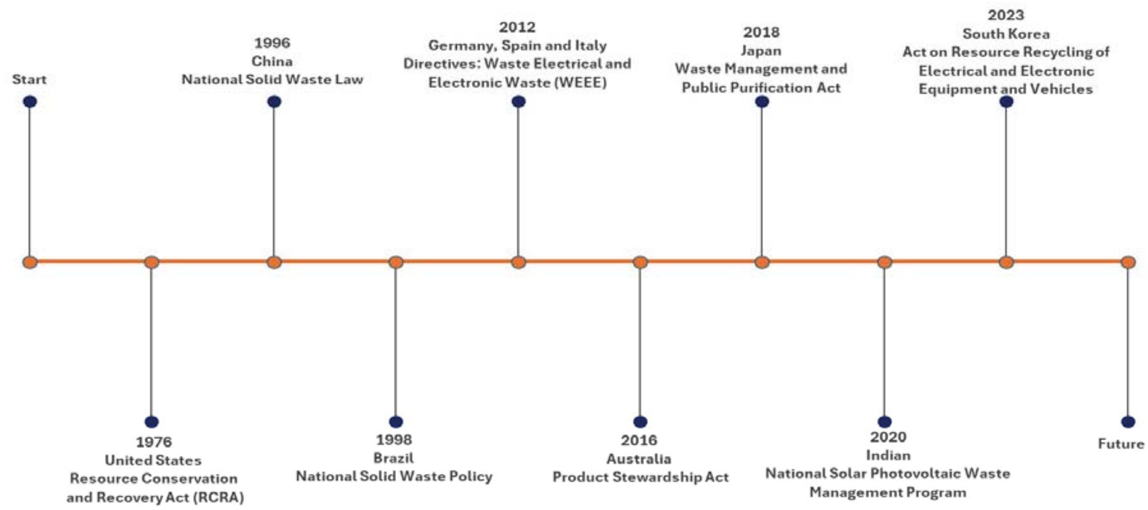


Figure 4 - Summary of existing legislation for the EoL management of PV. Source: Original work by the author, 2025.

EU – At the beginning of the analysis, it is worth highlighting the European Union, which includes Germany, Italy and Spain countries that appear in the global ranking of those with the highest installed solar generation capacity. These three countries are subject by Directive 2012/19/EU, which applies to all EU member states. Under this directive t, they are required to recover 85% of WEEE materials, of which 80% must be prepared for reuse and recycling. This responsability is assigned to manufacturers under the principle of extended producer responsibility (Official Journal of the EU, 2012).

China – China is the largest generator of photovoltaic solar energy in the world (IRENA, 2025), and it is also the leading manufacturer of photovoltaic solar panels (Clean Energy Portal, 2024). Despite this, there is still no specific legislation dedicated exclusively to the management of EoL solar photovoltaic panels (P. Majewski et al., 2020). Photovoltaic waste is included in the National Solid Waste Act, as well as in both mandatory (GB) and voluntary (GB/T) national standards (Amjad Ali., et al., 2023).

EUA – The United States ranks second only to China in the photovoltaic energy generation market. In 2024, its cumulative installed capacity reached approximately 175 GW (IRENA, 2025). Although it holds the second position in the ranking, there are no specific regulations addressing waste from solar power plants. In general, the final disposal of EoL from PVs is governed by the Resource Conservation and Recovery Act (RCRA) (Peter Majewski, et al., 2021). However, there are companies such as First Solar support a closed-loop system for solar modules. Additionally, some states are currently developing or adopting standards at the regional level, as is the case in California (Fortune Business Insights, 2025).
Indian – Since 2020, the country has had the National Solar Photovoltaic Waste Management Program, developed based on the Central Pollution Control Board (CPCB) Guidelines on the environmentally sustainable management of EoL solar photovoltaic waste, which have been in place since 2018 (P. Majewski et al., 2020). The Program is designed to estabilish a supply chain grounded in circular economy principles for photovoltaic waste, including the environmentally sound final disposal of EoL panels. Despite these regulations, challenges to full compliance remain, the existing infrastructure is still insufficient to handle the volume of waste generated by the solar industry (Ali et al., 2024).
Japan – The country does not yet have specific, mandatory legislation for the treatment of EoL photovoltaic solar panels (Ali et al., 2024). However, it is advancing initiatives to establish a voluntary recycling system aimed at mitigating environmental impacts and promoting the circular economy. EoL Solar panels are classified as industriais waste under the Waste Management and Public Cleansing Act. The law requires disposal in licensed facilities, but there are no specific legal requirements for recycling or reuse of these modules (P. Majewski et al., 2020).
Australia – In Australia there is still no mandatory federal legislation the EoL management of photovoltaic panels. However, the Product Stewardship Act 2011 was amended in 2016 to include PVs in the list of priority products for environmentally responsible final disposal. In some states, municipal regulations prohibit the disposal of panels in landfills and require them to be taken to designated collection points, for example, in Victoria (K. M. D. Nimesha, et al., 2024).
Brazil – In Brazil, the National Solid Waste Policy (PNRS) - Law No. 12.305/2010, establishes guidelines for the management of solid waste, including electrical and electronic equipment (EEE), which entails reverse logistics obligations for manufacturers (IBAMA, 2023.). However, given the current logistics infrastructure, end-of-life materials are still incinerated and/or sent to landfills (Dalla et al., 2020).
South Korea – South Korea incorporated PVs into its EPR system through the Recycling of Resources from Electrical and Electronic Equipment and Vehicles Act (PV CYCLE, 2025). Under this legislation, panel manufacturers and importers are responsible for the collection and recycling of panels. Since 2023, producers must recycle at least 80% of the collected panels, in line with EU targets (Lee, S.-H. and Jang, Y.-C., 2023).
Based on the analysis of the ten countries, it is evident that although most are making progress in managing the EoL of photovoltaic panels, significant disparities remain in terms of specific regulations. To date, there is no global authority or sector-specific entity that monitors and controls the disposal of panels at the end of their useful life. The European Union stands out with consolidated policies such as Directive 2012/19/EU, which imposes strict recycling targets under the EPR principle. China and the United States, although leaders in the generation and manufacture of solar modules, still lack specific national legislation for EoL, instead adopting broader guidelines such as the Solid Waste Act (China) and the RCRA (USA), with occasional pioneering initiatives at the state or corporate level. India and South

Korea have shown efforts through recent programs and legislation aimed at promoting the circular economy and meeting recycling targets. Japan and Australia are following voluntary and regional approaches, but without federal mandates to date. In Brazil, the PNRS establishes general guidelines, but there are still no specific regulations for the disposal of solar panels.
Overall, the global scenario indicates progress, but still uneven progress, highlighting the need for greater regulatory harmonization and the development of adequate recycling infrastructure to ensure that waste management in the solar photovoltaic industry is both technically and economically viable.

5 CONCLUSÃO

The growing adoption of photovoltaic solar energy, although essencial for the global energy transition, presents an urgent challenge in managing the waste generated at the EoL stage of solar modules. The research indicates that, despite advances in panel technologies up to the third generation, as well as improvements in recycling techniques and sustainable practices, there is still a lack of specific regulations and adequate infrastructure in several countries, which compromises the efficiency of environmentally sound final disposal processes. Therefore, the integration of public policies based on technical data, successful pioneering initiatives, and the principles of the circular economy is essential to structure robust regulatory models that can be adapted to the specif realities of each country. The EPR, combined with incentives for innovation and technological development, has emerged as a key strategy to enable large-scale recycling, ensure the reuse of valuable materials, and mitigate environmental impacts. Thus, a systemic, collaborative, and proactive approach is indispensable for consolidating a sustainable and resilient photovoltaic supply chain in line with global sustainability and decarbonization commitments.

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ASSESSMENT OF GREEN HYDROGEN AS A BACKUP ENERGY SOURCE FOR CIVIL DEFENSE STRUCTURES: TECHNICAL AND ENVIRONMENTAL FEASIBILITY FOR ENERGY TRANSITION IN CLIMATE RISK MANAGEMENT

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ABSTRACT

The worsening of disasters associated with climate change demands resilient and sustainable energy solutions to ensure the continuous operation of critical infrastructure, such as Civil Defense headquarters. Currently, these facilities rely primarily on diesel generators to supply emergency power, especially during extreme events, which often result in damage to the primary electricity grid.
This article aims to assess the technical and environmental feasibility of using green hydrogen as a backup energy source in disaster response operations, focusing on the replacement of traditional fossil fuel-based systems. Based on the disaster scenario analysis from the city of Petrópolis, RJ, a simulation is conducted of a backup energy system powered by green hydrogen, considering energy demand, autonomy time, storage volume, avoided emissions, and regulatory limitations.
The results indicate that green hydrogen is a promising alternative for the energy transition of critical risk management systems, offering emission reduction, operational safety, and alignment with the Sustainable Development Goals [7]. It is concluded that the adoption of this technology, although still incipient, can be enabled in strategic scenarios through specific public policies and pilot projects within the scope of Civil Defense operations.

KEYWORDS
Green hydrogen; Civil Defense; Backup energy.

INTRODUCTION

The increasing frequency and intensity of natural disasters observed in recent decades highlights the growing impacts of climate change on populations and critical infrastructure. Floods, landslides, severe storms, and heatwaves, among other extreme events, have challenged the response capacity of civil protection and defense systems, demanding increasingly robust, integrated, and resilient solutions.

In this context, the continuous availability of electricity becomes a strategic factor for the functioning of monitoring centers, emergency response units, temporary shelters, and early warning systems [6]. Power supply failures during disasters may compromise not only the coordination of response actions but also put thousands of lives at risk. Currently, most Brazilian Civil Defense structures that have backup power systems rely on diesel generators — a widely used technology, yet associated with several limitations, such as high greenhouse gas emissions, excessive noise, logistical dependence on fuel supply, and increasingly high operational costs.

Given the urgency of the energy transition and the search for low-carbon solutions, green hydrogen emerges as a promising alternative for decentralized and mission-critical applications. Produced from renewable sources through water electrolysis, green hydrogen generates no emissions during combustion or conversion, being considered a clean and versatile energy vector. Its application as a backup energy source for Civil Defense structures represents an opportunity to align environmental sustainability, technological innovation, and operational resilience.

This article aims to assess the technical and environmental feasibility of using green hydrogen as a backup energy source in Civil Defense facilities, focusing on critical operational structures that require uninterrupted power during emergencies. Based on a case study in the city of Petrópolis (RJ), different energy sizing scenarios are simulated, comparing the current solutions with hydrogen-based systems. The goal is to contribute to the development of sustainable alternatives for disaster risk management in Brazil, paving the way for pilot projects and public policies that foster innovation in the sector.

To this end, a comparative case study was developed between two energy systems: one based on a diesel generator and the other on a fuel cell powered by green hydrogen. The analysis used technical, environmental, and operational criteria, drawing from simulated data and references from specialized literature.

TECHNICAL FRAMEWORK AND TECHNOLOGICAL CONTEXT

The adoption of resilient energy systems in disaster response structures is a topic of growing international interest, driven both by the impacts of climate change and by technological advances in the energy sector. The specialized literature highlights that, in crisis scenarios, the continuous supply of electricity to command and control centers, communication systems, and temporary shelters is a decisive factor for the effectiveness of emergency response. Therefore, backup solutions with high reliability and a low carbon footprint are essential to strengthen the critical infrastructure of civil protection.

The most common model for emergency power supply at Civil Defense headquarters in Brazil is still based on diesel generators, which activate automatically when the grid fails. Although they are robust and easy to operate, these systems present a number of issues: they emit large amounts of CO_2 and particulate matter, produce high noise levels, pose leakage risks, and depend on a vulnerable fuel supply chain—especially in disaster scenarios. Furthermore, growing pressure for decarbonization and the demand for more sustainable solutions have encouraged a reevaluation of fossil fuel use in essential public services.

In this context, green hydrogen emerges as an increasingly viable option. Produced through water electrolysis using electricity from renewable sources (such as solar and wind), it can be stored in pressurized tanks and later converted back into energy via fuel cells—or, in some cases, adapted combustion engines. Its main advantage lies in the absence of pollutant emissions during use, in addition to long-term storage capabilities that overcome many of the limitations of conventional batteries.

Several studies and pilot projects around the world have demonstrated the technical feasibility of hydrogen-based systems for decentralized and off-grid applications [5][9]. In Japan, for instance, community centers and hospitals have been equipped with hybrid systems combining solar power and fuel cells to ensure uninterrupted operation during earthquakes or prolonged blackouts. In Europe, initiatives aimed at decarbonizing emergency services have also incorporated hydrogen as a strategic component.

However, the adoption of this type of technology in Civil Defense structures is still incipient in Brazil, due both to the lack of specific incentives and to technical, economic, and regulatory limitations. In this context, assessing the feasibility of green hydrogen as an alternative to diesel generators is an important step toward informing public policies focused on innovation and sustainability in risk management.

In this regard, the National Hydrogen Program (PNH2), launched in 2021 by the federal government, stands out as a strategic initiative aimed at fostering the development of the hydrogen value chain in Brazil. The plan includes actions related to research, development, regulation, and infrastructure, which may significantly contribute to mitigating barriers and accelerating the adoption of hydrogen-based technologies in the public sector.

The next section presents the methodology adopted to simulate the application of green hydrogen in a real Civil Defense facility, detailing technical parameters, operational data, and comparison criteria for the analyzed solutions.

METHODOLOGY AND CASE STUDY

This study adopts a case study approach combined with technical simulation and comparative analysis to assess the technical and environmental feasibility of using green hydrogen as a backup power source for Civil Defense structures. The chosen case is the operational headquarters of the Civil Defense agency in Petrópolis, a municipality in the state of Rio de Janeiro, Brazil.

The selection of Petrópolis is justified by its strategic relevance in the context of hydrometeorological disasters in the country—particularly due to the catastrophic events of February 2022, when severe floods and landslides disrupted basic services and caused prolonged power outages across several districts. This real-world context provides a representative scenario for evaluating energy resilience solutions.

The methodology involves the following steps:

- Characterization of the energy demand of the Petrópolis Civil Defense headquarters, based on technical information provided by local authorities;
- Simulation of two backup energy systems: a conventional diesel generator and a system based on green hydrogen using proton exchange membrane (PEM) fuel cells;
- Comparative analysis of technical parameters, such as power capacity, autonomy, maintenance requirements, environmental impact (CO_2 emissions and noise), and operational reliability;
- Estimation of the Total Cost of Ownership (TCO) for each system, considering a 15-year operational horizon;
- Use of qualitative and quantitative evaluation tools, including a multicriteria radar chart developed in Python (Matplotlib), to synthesize performance indicators and support strategic decision-making.

This structured methodological framework aims to bridge technical analysis with real-world constraints and institutional readiness, offering practical insights for implementing clean backup energy solutions in critical public infrastructures.

Evaluated Structure

The Civil Defense headquarters of Petrópolis operates as the municipality's primary command and control center in disaster situations, requiring continuous and autonomous functioning of its technological infrastructure. The facility houses a digital monitoring panel that aggregates real-time feeds from urban surveillance cameras distributed throughout the city. In addition, it supports approximately 40 computers, radio transceivers (HF and VHF), television screens for institutional bulletins, lighting circuits, network servers, and auxiliary communication systems. These components are essential for coordinating emergency response, disseminating alerts, managing logistics, and maintaining communication with field teams and other government agencies.

Considering this operational profile and the 24/7 nature of the activities performed during disaster events, the facility presents an estimated average electrical demand of 4 kW. To ensure continuity of service during grid failures, especially in adverse scenarios such as floods or landslides, the minimum required autonomy for a backup system is 48 hours. This implies the need for an alternative energy solution capable of supplying at least 192 kWh in this period, already accounting for energy conversion losses inherent in battery banks, inverters, or fuel cell systems. The system must also be reliable, easily manageable during emergencies, and compatible with safety standards applicable to critical infrastructure.

Reference Scenario (Diesel System)

For comparison purposes, the system currently used by the facility is considered. It consists of a diesel generator with a nominal capacity of 7.5 kVA (6 kW), consuming an average of 1.6 liters of diesel per hour under partial load. To keep the headquarters operational for 48 hours, approximately 77 liters of diesel would be required, resulting in estimated emissions of around 204 kg of CO_2 (considering 2.65 kg CO_2 per liter of diesel).

Proposed Scenario (Green Hydrogen System)

In the simulation of the green hydrogen system, a Proton Exchange Membrane Fuel Cell (PEMFC) was considered, with an average efficiency of 50%. To meet the 192 kWh demand, approximately 384 kWh of chemical energy stored in hydrogen would be required, equivalent to about 11.5 kg of H_2, considering a lower heating value (LHV) of 33.3 kWh/kg.

The simulated system includes:

- A hydrogen generation unit via electrolysis, powered by an on-site photovoltaic solar system;
- H_2 storage tanks at 350 bar;
- A 5 kW continuous fuel cell;
- Energy management system and inverters.

Evaluation Criteria

The two scenarios were compared based on the following criteria:

- **Technical feasibility**: load coverage capacity, autonomy, scalability, and reliability;
- **Environmental performance**: greenhouse gas emissions and noise;
- **Operational aspects**: ease of operation, logistics, maintenance, and safety;
- **Estimated cost**: initial investment, operating and maintenance costs;
- **Regulatory compliance**: compatibility with Brazilian and international standards.

The data were organized into a comparative matrix presented in the next section, with the aim of identifying the advantages, limitations, and application potential of green hydrogen as a backup solution for critical Civil Defense infrastructure.

TECHNICAL AND ENVIRONMENTAL FEASIBILITY ANALYSIS

Based on the two simulated scenarios—the conventional diesel system and the innovative green hydrogen-based system—this section presents a comparative analysis of the technical, environmental, and operational aspects, considering the real context of a Civil Defense structure during climate emergency response operations.

Table 1. Comparison between diesel system and green hydrogen system for backup power supply in Civil Defense headquarters

Criterion	Diesel System	Green Hydrogen System
Load capacity	Meets demand (6 kW nominal)	Meets demand (5 kW fuel cell)
Autonomy	48h with 77 liters of diesel	48h with ~11.5 kg of H_2
CO_2 emissions	~204 kg over 48h	Zero emissions at point of use
Noise level	High	Nearly silent
Maintenance	Frequent (oil, filters, mechanical parts)	Low (no critical moving parts)
Logistics complexity	High (external fuel supply required)	Medium (prior production or refueling needed)
Estimated initial cost	~R$ 75,000	~R$ 250,000 to R$ 400,000
Operational cost	High (fuel and spare parts)	Low (renewable production, minimal maintenance)
Life cycle	5 to 10 years	10 to 15 years
Environmental suitability	Poor (fossil fuel, local emissions)	Excellent (low carbon footprint)
Regulatory framework	Established	Under development
Emergency response time	Immediate (few seconds)	Variable, may take several minutes

Technical Feasibility

Both systems evaluated are technically capable of meeting the demand of 192 kWh over 48 hours, albeit with distinct operational characteristics.

The diesel generator presents advantages such as immediate commercial availability, operational simplicity, and operator familiarity. However, its autonomy is directly dependent on the continuous supply of fuel, which may pose a risk in disaster contexts where road access and logistics are compromised.

In contrast, the green hydrogen-based system offers greater structural autonomy and lower vulnerability to external logistics, as the fuel can be produced and stored in advance. The fuel cell operates silently, with no mechanical vibrations and high reliability, making it ideal for urban and critical environments. Its performance, however, depends on a pre-existing infrastructure for generation, storage, and conversion, which is still incipient in Brazil.

Environmental Assessment

From an environmental standpoint, the comparison between the two backup systems reveals substantial differences in emissions, local pollution, and compatibility with Brazil's climate commitments. The diesel system, widely used in critical infrastructure, is also one of the most polluting in this context. To meet the simulated 192 kWh energy demand over 48 hours, an estimated 77 liters of diesel are required, resulting in approximately 204 kg of CO_2 emissions, in addition to NO_x, SO_2, CO, and PM2.5 particles, all of which impact both climate and public health [8].

Additionally, diesel generators produce high noise levels and operational risks, such as fuel leaks and environmental contamination. In contrast, the green hydrogen system offers zero emissions at the point of use, provided the hydrogen is produced from renewable sources (solar or wind). Its operation is silent, pollutant-free, and does not require additional inputs, making it suitable for urban centers and sensitive environments.

By adopting this solution, public facilities align themselves with the Sustainable Development Goals (SDGs 7, 11, and 13), contributing to carbon neutrality and local pollution reduction, in accordance with Brazil's Climate Plan and the Paris Agreement [1].

Multicriteria Evaluation of Backup Systems

Figure 1 presents a comparative evaluation between diesel and green hydrogen energy generation systems using five key criteria: CO_2 emissions, noise, maintenance, logistics, and environmental impact. Each criterion was rated on a scale from 1 (poorest performance) to 5 (best performance), based on qualitative analysis and technical benchmarks. All criteria were considered equally weighted, as they represent relevant and complementary dimensions in the operation of critical facilities such as Civil Defense units.

The radar chart was generated using Python's Matplotlib library, providing a clear visual representation of the performance differences between the alternatives. The green hydrogen system shows superior scores in environmental and logistical criteria, whereas the diesel generator holds a slight advantage in maintenance simplicity. This multicriteria approach contributes to supporting informed technical decisions for energy transition within the public sector.

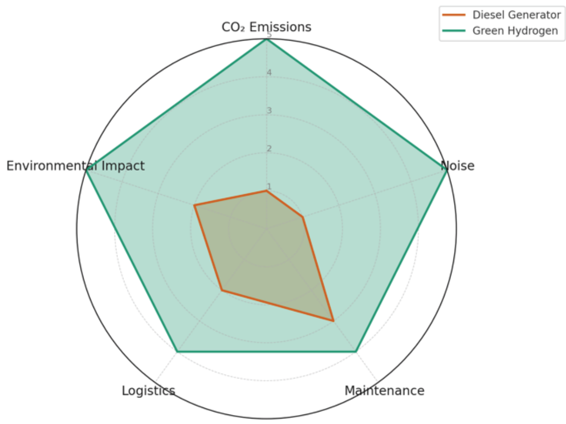

Figure 1. Multicriteria Evaluation of Backup Systems Using Diesel and Green Hydrogen

It is observed that the green hydrogen system achieved maximum performance in nearly all criteria, notably for zero CO_2 emissions, silent operation, and strong alignment with environmental guidelines. On the other hand, the main challenges are related to logistical complexity and the need for specialized maintenance, reflecting the lower technological maturity and still-nascent infrastructure for hydrogen production, storage, and operation in the Civil Defense context.

The diesel system, although offering logistical advantages and requiring less immediate maintenance, performs poorly in environmental and operational criteria, especially regarding high emissions and significant acoustic impact during operation.

This evaluation reinforces the technical and environmental feasibility of transitioning to sustainable backup systems in Civil Defense structures, particularly in medium and long-term strategies.

Economic Assessment: Total Cost of Ownership (TCO) and Economic Sustainability

Although the acquisition cost of a green hydrogen-based system is significantly higher—ranging from R$ 200,000 to R$ 400,000 depending on size and technology—this initial analysis does not adequately reflect the real cost over the system's life cycle. For this comparison, a 15-year operational horizon was considered, based on durability and maintenance estimates for each technology [3]. According to market estimates and recent global project databases [4], the total investment includes the fuel cell, pressurized tanks, electrolyzer, inverters, and control and integration systems, explaining the cost range found in small-scale systems aimed at energy resilience.

The diesel generator, with an estimated cost of R$ 75,000, requires frequent maintenance, filter replacement, high fossil fuel consumption (about 60 liters per 8-hour cycle), and refueling logistics—which is particularly critical in disaster scenarios. When considering cumulative diesel costs, maintenance, and possible replacements, the 15-year total may exceed R$ 250,000.

On the other hand, the green hydrogen system presents significantly lower operational costs after installation, as it does not require frequent refueling and demands less intensive maintenance. Additionally, integration with solar sources and the potential for tax incentives or carbon credits could further reduce the system's effective long-term cost.

Institutional Innovation and Climate Leadership of Civil Defense

Integrating clean and resilient energy sources into Civil Defense structures represents more than a technical solution—it is a strategic choice that reinforces the institution's role in the environmental agenda and climate change response. By investing in solutions such as green hydrogen, Civil Defense not only ensures response capacity during adverse scenarios but also establishes itself as an institutional reference in climate innovation.

This type of initiative goes beyond the traditional role of Civil Defense in emergencies. By adopting clean energy sources, it influences the public sector sustainability debate. If well communicated, such projects can attract the interest of universities, international funders, and contribute to stronger public policies.

Challenges, Limitations, and Opportunities

The introduction of green hydrogen-based technologies in public disaster response structures, such as Civil Defense headquarters, requires not only technical and environmental feasibility but also overcoming a complex set of institutional, regulatory, financial, and cultural limitations. This section analyzes these challenges and proposes possible mitigation pathways.

Technical and Logistical Limitations

The main limitation for adopting green hydrogen-based backup systems in Brazil lies in the still-incipient infrastructure for hydrogen production, storage, and distribution. The lack of consolidated logistics chains, combined with a scarcity of national suppliers of equipment such as fuel cells and high-pressure tanks, increases costs and implementation complexity [2].

Additionally, the shortage of trained technicians and the need for specific safety protocols—including handling gases under high pressure and proper ventilation—present further barriers. For Civil Defense applications, where reliability and rapid response are essential, the technology learning curve must be carefully managed through training, institutional partnerships, and gradual adoption.

Economic and Regulatory Limitations

The high upfront cost of hydrogen systems, coupled with the absence of tax incentives or specific financing lines, limits their competitiveness compared to traditional solutions. Brazilian legislation still lacks clear regulatory frameworks for decentralized hydrogen production and its use in public facilities. This regulatory uncertainty may create legal insecurity and discourage investment.

Furthermore, the role of Brazilian regulatory agencies in consolidating this technology must be considered. ANEEL has promoted studies and public consultations on hydrogen's inclusion in the national power grid, while ANP has initiated discussions on regulatory frameworks for hydrogen production, transportation, and storage. Although still at early stages, these initiatives indicate a promising path toward clearer norms capable of enabling pilot projects and fostering institutional adoption of this energy source for critical State functions.

Another barrier lies in public procurement processes, which often favor established, low initial-cost technologies without considering long-term environmental and operational benefits.

Opportunities for Innovation and Cooperation

Despite the challenges, implementing green hydrogen systems in Civil Defense may represent a strategic opportunity window. Command structures—such as monitoring centers and shelters—serve as real laboratories for demonstrating clean technologies applied to life protection.

There is potential for:

• Partnerships with universities and research centers for pilot projects and field testing;

• Agreements with energy sector companies and hydrogen-focused startups;

• Fundraising through national and international innovation calls, such as the National Climate Change Fund or programs from the UN and European Union;

• Development of integrated public policies aligned with urban resilience plans, electric mobility, and climate neutrality goals.

Additionally, by adopting sustainable solutions, Civil Defense can strengthen its role as an institutional transformation agent and environmental educator, promoting a culture of sustainability in the public sector.

CONCLUSIONS

This study analyzed the technical and environmental feasibility of using green hydrogen as a backup energy source in Civil Defense structures, using the operational headquarters in Petrópolis (RJ) as a reference. The comparative simulation with the conventional diesel system demonstrated that, although hydrogen-based technology still faces significant challenges in Brazil—such as high initial costs, lack of logistical infrastructure, and regulatory limitations—it represents a promising alternative in the context of energy transition toward a low-carbon economy.

The results indicate that adopting fuel cell systems powered by green hydrogen can offer significant environmental advantages, including zero pollutant emissions, silent operation, and greater structural autonomy, which directly contributes to the energy resilience of command centers during disasters. Furthermore, the use of clean technologies in critical structures reinforces Civil Defense's institutional role as a driver of transformation and innovation in the public sector.

It is recommended to implement pilot projects in strategic cities, create specific financing lines for climate resilience innovation, and update regulatory frameworks for green hydrogen in Brazil. The convergence of sustainability, energy security, and civil protection should guide the next steps toward a more robust, cleaner, and climate-ready disaster risk management model.

In addition to the direct operational benefits, the adoption of green hydrogen in Civil Defense facilities has the potential to inspire broader institutional change. By serving as real-world laboratories for clean energy technologies, these centers can catalyze research and development, stimulate public-private partnerships, and promote a culture of innovation in emergency management. As climate-related disasters become more frequent and intense, integrating sustainable energy solutions into risk governance frameworks will be not only desirable—but indispensable.

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PHOTOVOLTAIC SOLAR DEHYDRATOR: A SUSTAINABLE ALTERNATIVE FOR INCOME GENERATION FOR SOCIALLY VULNERABLE POPULATIONS

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ABSTRACT

This article presents a proposal for creating a social technology that involves reusing discarded fruit and adapting a homemade food dehydrator model produced by EMBRAPA. This adaptation combines direct sunlight exposure during the day and electrical energy stored in batteries at night (captured by solar panels during the day). This energy is used to perform two simultaneous processes: heating and ventilation. The research was developed based on a request from a group of refugees who participated in a training course offered by an educational institution in Rio de Janeiro, Brazil, on food production for job and income generation. This article seeks to demonstrate the significant income-generating potential of this social technology.

KEYWORDS

Photovoltaic solar dehydrator, income generation, social technology, renewable energy.

INTRODUCTION

Starting a new life in another country is a challenge experienced daily by thousands of people around the world. The difficulty for people in refugee situations is quite acute. This new beginning is fraught with numerous challenges: sociocultural barriers to entering the formal job market, difficulty in having diplomas recognized, and the difficulty of building social networks (social capital). There is a loss of connection with the country of origin and the social and cultural novelty of a new country (Herima et al., 2021). Given this scenario, one alternative is the development of quick and affordable income-generating solutions, especially those that can be implemented in the short term. This article proposes the creation of social technology that can offer solutions to the problem of generating work and income for vulnerable populations. The project's goal is for this technology to be low-cost and replicable anywhere in the world.

The project was motivated by a food production training program developed by a Brazilian university for refugees with support from the UNHCR and humanitarian organizations. The initiative received financial support from CAPES through the PROEXT-PG grant, which encompasses research and university extension initiatives. The training involved the selection of fifteen refugees from Venezuela, Cuba, Colombia, and the Democratic Republic of Congo.

The training was held in the city of Valença, in the interior of the state of Rio de Janeiro, Brazil, where the university offers a Food Engineering program. The campus has its infrastructure for teaching and research in this field and has been interacting with local industry, playing an essential role in regional development. The training covered several theoretical topics, such as good handling practices of food and food safety. The practical part included presentations on the production processes for bread, pizza, jellies, preserves, candied fruit, and dried fruit.

During the practical activities, it was discovered that the fruit dehydration process offered the best cost-benefit ratio for commercialization. The fruit is cut into strips and undergoes a dehydration process that transforms it into natural "chips." In large Brazilian cities, there is a high demand for this type of product. On the other hand, the raw material can be obtained almost free of charge, as producers or sellers discard many fruits due to blemishes or deformities generated during harvesting or transportation. These local deformities invalidate the entire fruit for the consumer. This information sparked significant interest among participants, especially given the high market value of dehydrated fruits and the low investment required to obtain the raw material.

During the training, the fruits were dehydrated using an electric dehydrator that uses heating and ventilation in a 24-hour process. However, the possibility of building a low-cost homemade dehydrator that, through exposure to the sun, completes the process in four days was also presented. It has been a long time since it came to commercialization. The idea then arose of building an electric dehydrator that combined exposure to the sun during the day and could continue the process at night using renewable energy.

From this need, a research/university extension project called "Construction of a Fruit Dehydrator for People in Refugee Situations" was created. The central objective is to develop this social technology and subsequently provide training in the construction of equipment for socially vulnerable populations who need to undertake projects to generate income in the short term. The objectives of this project go beyond the construction of an artifact; they also intend to create a process for reusing discarded semi-damaged fruit, thereby extending its life cycle as a product. Therefore, social technology goes beyond the artifact itself, constituting a process for reusing what was previously considered waste.

This article aims to demonstrate the initial economic feasibility studies of this social technology. The proposal seeks to constitute a social innovation, not only by introducing the use of renewable electricity in the device, but also by creating ways to generate work and income for vulnerable populations through the reuse of fruit waste. In this way, the initiative emphasizes the promotion of economic, social, and environmental sustainability by meeting UN SDGs 1, 2, 3, 7, and 8.

THEORETICAL FRAMEWORK

Social Technology (ST) is associated with the creation of new products, services, processes, methodologies, and organizational structures aimed at solving real social problems. It is a technology geared toward local realities, leveraging the collective creativity of experts and communities affected by the issue. Furthermore, it must be geared toward economic sustainability, ensuring the financial viability of the enterprise (DAGNINO, 2014). ST can also be considered a viable alternative to development, as it carries premises and potentialities capable of challenging prevailing development models (KAHLÂU et al., 2019). The interaction between society, the state, and universities is fundamentally essential for the design and sharing of social technologies, as it enhances the exchange between knowledge produced in academia and traditional knowledge produced locally (GORANSSON et al., 2021). Studies also show that community appropriation of technology promotes local autonomy through participatory citizen science. (HSU; NOURBAKHSH, 2019). TS, when developed in conjunction with the local community, can span several areas of knowledge, including the Circular Economy (CE), the foundation of sustainability.

The Circular Economy emerges as a sustainable, regenerative, and restorative development model, focused on maintaining resources, including food, at their highest level of usefulness and value over time. It also proposes a production model that extends the life cycle of resources, breaking with the linear model of extraction, production, and disposal (OURO SALIM, GUARNIER, LEITÃO, 2021).

In this context, food waste, especially perishable food waste, represents a critical challenge, being one of the main social and environmental problems of recent times, affecting the sustainability of food systems (CASONATO et al., 2023). It is within this perspective that the proposal to develop and share a photovoltaic solar dehydrator fits in, as an affordable technological alternative to address this problem.

Fruit dehydration is part of the circular economy concept, as it helps reuse food that would otherwise be discarded, extending its life cycle and adding value to the product. Furthermore, dehydrated foods extend the life cycle of perishable products, enabling more time-consuming distribution logistics. In this sense, CE represents a challenging proposition, as it seeks to dissociate economic growth from the high consumption of natural resources and environmental degradation (KIRCHHERR et al., 2023).

The use of the fruit dehydration process implies a paradigm shift, as by extending the shelf life of food that would otherwise be discarded, its trajectory within the production system is reconfigured. This logic aims for a resilient and ecologically balanced future, through a mindset that requires the transformation of business models and consumption patterns (HENDERSON, 2023).

METHODOLOGY

The methodology used involves the involvement of university students, professors, and technicians, as well as community members, and actively listening to people in refugee situations to develop a low-cost technological solution.

During the training, a manual for building a low-cost fruit dehydrator based on a model created by the Brazilian Agricultural Research Corporation (EMBRAPA) was presented. The dehydrator uses electricity for both heating and ventilation. Since much of Brazil is served by a vast electricity grid, the presented model did not consider the energy source, which can be obtained through the utility companies' supply network. However, considering that many people do not have access to electricity from a distribution network, the team proposed an adaptation that could utilize direct sunlight for heating and natural ventilation during the day. At night, the process would continue using electricity from the stored energy in a battery through a solar energy capture system implemented during the day.

The project's innovation lies in its use of two cycles, one daytime and one nighttime, instead of a single cycle powered by grid electricity (day and night). The model proposed by Cornejo (2018) uses a single heater with dual heating and drying functions, powered by electricity. The dual-cycle function was designed within the context of the energy transition and targeted at communities with limited access to the electricity grid.

Some adjustments are necessary to enable direct solar radiation heating in the model suggested by Cornejo (2018), such as painting the inside and outside of the Styrofoam box with black paint to increase heat absorption/emission and installing a glass lid on top, creating a greenhouse.

According to the EMBRAPA manual, banana drying should occur at a temperature of 60°C and an estimated waiting time of 15 to 20 hours for the dehydration of 6 kg of bananas. The challenge is maintaining a temperature close to 60°C at night, as blown heating can consume a lot of energy, which would require more expensive equipment.

EXPECTED RESULTS

As mentioned previously, the prototype of the photovoltaic solar dehydrator with hybrid operation is currently under construction and was designed based on the low-cost model developed by EMBRAPA. The proposed structure includes four metal trays (36 cm × 30 cm), with an estimated capacity of 6 kg of fruit per cycle, and thermal insulation using an 80-liter Styrofoam box.

Production Estimates and Economic Projection

As described in the EMBRAPA manual, the artisanal dehydrator proposed by Cornejo (2018) can produce 2 kg of dehydrated bananas at the end of a process lasting up to 20 hours, using 6 kg of peeled bananas, which originally weighed approximately 12 kg with the peel.

The EMBRAPA system was designed to operate continuously in different weather conditions, using electricity from the grid, on rainy, cloudy, and nighttime days. Considering that a 30-day month has 720 hours and that a daily production cycle would be completed, assuming 20 hours of fruit dehydration plus 4 hours for packaging, sanitization, and preparation of the new crop. In this scenario, it is possible to project 30 production cycles of 2 kg of dehydrated bananas per month. Therefore, within this context, a total production of approximately 60 kg of dehydrated bananas per month is estimated.

The market price of dehydrated bananas varies widely. At street markets, which are the most likely sales channel for the students participating in the project, a 100g package can be sold for prices ranging from R$10.00 to R$20.00, which is equivalent to R$100.00/kg (or €15.4) to R$200.00/kg (or €30.8) per kilogram.

Therefore, the gross monthly revenue projection (without considering input and packaging costs) can vary between R$6,000.00 (60 kg × R$10.00/100g) and R$12,000.00 (60 kg × R$20.00/100g).

Estimated Cost of the Photovoltaic Electric Dehydrator

The estimated total cost of the equipment, based on prices in effect in July 2025, is shown in the following table:

Item	**Quantity**	**Unit cost (july 2025) (R$)**	**Subtotal (R$)**
80-liter Styrofoam box	1	100,00	100,00
Black paint	1	20,00	20,00
PVC pipes (piece 3m long 25mm)	2	30,00	60,00

Bent pipe (90°) with 25cm	8	2,00	16,00
T-shaped connections (25cm)	4	8,00	32,00
Nylon net	2	10,00	20,00
Electric heater	1	130,00	130,00
100W solar panel	1	150,00	250,00
Charge controller	1	40,00	40,00
Charge controller	1	60,00	60,00
Total cost			**728,00**

Table 1: Estimated cost of photovoltaic electric dehydrator.

Since the photovoltaic solar dehydrator can be fully utilized without increasing residential electricity consumption on sunny days, the manufacturing and assembly costs (excluding labor costs) of the equipment are compatible with the values of social technology and are viable in low-income communities. The proposed hybrid model could be used in locations with or without access to electricity, promoting income generation even in highly vulnerable areas.

Estimated Production Costs

The primary concern regarding the fruit dehydration process is the cost of purchasing fresh produce or the high cost of electricity. In July 2025, in the city of Rio de Janeiro, where the university coordinating this research is located, the average price per kilogram of bananas was R$4.00. The cost of electricity, for using a portable electric heater, according to the manual produced by EMBRAPA, has an average consumption of 1.5 kWh for every 2 kg of bananas obtained. Knowing that the amount charged for electricity consumption in Rio de Janeiro is R$1.12 per kWh in July 2025, we can calculate using the equation:

2 kg of dehydrated bananas = 1 day of production = 1.5 kWh of average consumption.

1) Daily cost: Energy consumption = 1.5 kWh x R$1.12 = R$1.68

2) Monthly cost: Energy consumption = 1.68 x 30 = R$50.40

The following table shows the input costs to produce dehydrated bananas:

Item	**Quantity per production cycle**	**Unit Cost (R$)**	**Cost per cycle (R$)**	**Monthly cost (30 production cycles) (R$)**

Fresh banana	12 Kg	4,00[1]	4 x 12 = 48,00	48 x 30 = 1.440,00
Electric Energy	50% dos ciclos	1,12[2]	1,5 x 1,12 = 1,68	1,68 x 30 = 50,4 50,4 / 2 = 25,2
Packaging	20	0,3	6,00	6 x 30 = 180,00
Total production cost / month				**1.645,20**

Table 2: Estimated cost of producing dehydrated bananas.

We can therefore conclude that the estimated monthly production cost of dehydrated bananas, considering that the heater will be on only 50% of the production time, is approximately R$1,645.20.

Therefore, after calculating the production costs, we can estimate the potential profit from selling dehydrated bananas, assuming all units are sold and the producers already cover fixed costs, as this is a domestic production process designed to generate additional income. Therefore, we can have two scenarios, as shown in the table below:

Scenario	**Gross Income (R$)**	**Monthly Costs (R$)**	**Net Income (R$)**
Conservador	6.000,00	1.645,20	**4.354,80**
Otimista	12.000,00	1.645,20	**10.354,80**

Table 3: Estimated Net Income

It is important to emphasize that production costs can be drastically reduced by purchasing bananas that are not up to market standards. This can be achieved through partnerships with supermarkets and market vendors. Other fruits can be dehydrated and sold, but bananas were used only as an example in this article.

CONCLUSION

This article sought to demonstrate the importance of universities' role in examining society's problems and working collaboratively to solve them. The overall objective of the study was to demonstrate the possibility of creating technologies aimed at generating work and income for people in socially vulnerable situations, both those seeking refuge in another country and those already established in a region.

The financial projections presented in a more conservative and a more optimistic scenario show that dehydrating and selling fruit using a photovoltaic solar dehydrator can become an important source of income. The innovation proposed in this article aligns with the increasingly necessary concept of energy transition and proposes a new approach by

[1] Value based on the city of Rio de Janeiro, Brazil, in July 202
[2] Value charged by the electricity company in the city of Rio de Janeiro in July 2025.

incorporating the possibility of using solar energy to dehydrate fruit and a model for reusing fruit waste, a common practice in markets and fairs.

The next steps of the project begin with the construction of the prototype suggested in this article and the execution of bench tests, both for the efficiency of dehydrated fruit production and for the safety and durability of the equipment.

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INTEGRATED CIRCULAR ECONOMY STRATEGIES FOR WASTE VALORIZATION IN UNIVERSITY CAMPUSES: A HYPOTHESIS-BASED FRAMEWORK

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ABSTRACT

Higher education campuses generate diverse organic waste streams, including food wastes, used cooking oils, and lignocellulosic biomass, that present opportunities for circular economy implementation. This paper proposes a conceptual, decentralized framework integrating three complementary valorization technologies: anaerobic digestion of food waste, (trans)esterification of used cooking oils, and pyrolysis of lignocellulosic residues. Each component targets energy self-sufficiency and resource recovery, while offering pedagogical and community engagement benefits. Treated food waste produces biogas for electricity or heat and digestate for soil enrichment, while used oils can be converted into biodiesel to power campus systems, and lastly, biomass can be pyrolyzed to yield biochar, which may enhance digestate quality or act as a carbon sink. This framework is positioned as a scalable, replicable model for institutional sustainability in rural or under-resourced regions and includes evaluation pathways in terms of technical, environmental, economic, and social performance. Future pilot studies could validate its feasibility and contributions to climate mitigation and circular nutrient cycles.

KEYWORDS

Circular economy, Waste valorization, Anaerobic digestion, Biodiesel, Pyrolysis, Higher education, Infrastructure hypothesis.

INTRODUCTION

University campuses (UCs) produce a variety of waste flows from cafeterias, facilities maintenance, laboratories, and landscaping operations. The concept of the circular economy (CE) offers a framework for minimizing waste and maximizing resource reuse by redefining production and consumption models [1]. As such, campuses are uniquely positioned to serve as living laboratories for CE implementation, reinforcing academic curricula and influencing future generations.

Recent growth in academic interest reflects four core CE strategies: the integration of renewable energy, the elimination of harmful substances, process redesign for waste reduction, and the development of secondary raw material markets [2]. While the theoretical groundwork is robust, practical implementation in institutional contexts remains scarce. UCs are recognized as strategic agents for sustainability transformation, given their mission, resources, and community influence [3]. The urban metabolism framework, when adapted for campuses, reveals potential efficiency gains by reducing resource inputs and emissions. Cornell

University's composting pilot reduced CO_2 emissions by 16–39 t/year and generated net financial benefits. Yet, a recent systematic review found limited examples of coordinated CE application at the institutional level [4].
Case studies in developing regions reinforce this gap. At the Federal University of Technology, Akure (FUTA), Nigeria, waste streams rich in polyethylene and paper were identified as suitable for colour-coded sorting and recycling partnerships [5]. Mendoza et al. [6] proposed a PDCA (Plan–Do–Check–Act) method, applied at the University of Manchester, to embed CE principles in campus sustainability, demonstrating structural improvements. These studies underline the potential of UCs to lead CE adoption, but highlight limitations in practical, multi-stream implementation models.
This paper proposes a hypothesis-driven, multi-technology system designed to add value to campus-generated organic waste, thereby reducing carbon footprint, closing resource loops, and offering educational value.

Material and energy valorization as waste management tools

Valorization is a cornerstone of CE, seeking to recover material or energy from waste and thus reduce landfill use and greenhouse gas (GHG) emissions. Material recovery is preferred, but energy recovery remains valuable under suitable conditions [7]. In the context of this work, literature surveys have focused on research conducted on three technological pathways: anaerobic digestion (AD), (trans)esterification, and pyrolysis.
AD converts organic waste into biogas and digestate via microbial processes. Studies confirm its efficiency with food waste and agricultural residues and that co-digestion strategies and biochar addition can mitigate inhibition and boost biogas yields [8][9]. Digestate itself can serve as a fertilizer or feedstock for pyrolysis, converting nutrient-rich residues into biochar [10].
(Trans)esterification transforms used oils into biodiesel, which is comparable to diesel fuel in viscosity. This process is highly efficient under low-acidity conditions, though pretreatment may be necessary for oxidized or high-acid-content oils [11]. Innovative catalysts, such as biomass-derived materials or shell-based solids, enhance yield and sustainability [12]. Glycerol, a by-product, can be further valorized (e.g., into biomethanol or high-value chemicals), strengthening the economic viability of biodiesel systems [13].
Lastly, pyrolysis thermochemically decomposes dry biomass or digestate in low-oxygen environments to produce biochar, bio-oil, and syngas. Product yields depend on feedstock and operational conditions [14]. Fast pyrolysis of pine and eucalyptus residues yields combustible biochar suitable for soil amendment or fuel replacement, with emerging studies emphasizing biochar's role in soil conditioning, fuel applications, and adsorbent functions [15].
Together, these technologies form a complementary cluster capable of recovering energy and materials from multiple waste streams on campus, contributing to a resource-efficient closed-loop system.

CONCEPTUAL FRAMEWORK

The hypothesis proposes an integrated system combining AD, (trans)esterification, and pyrolysis at campus scale. Food waste undergoes AD, yielding biogas for local energy production and digestate for nutrient recovery. Digestate solids or lignocellulosic biomass wastes enter pyrolysis units to produce biochar, which in turn can enhance digestion performance or improve student experimental applications in soil science. Used cooking oils are processed through (trans)esterification to produce biodiesel, which can fuel stationary combined heat and power (CHP) systems or dual-fuel engines on campus. This approach is illustrated in Figure 1, which depicts a detailed process flowchart for each technology, including inputs, outputs, and feedback loops among its components.

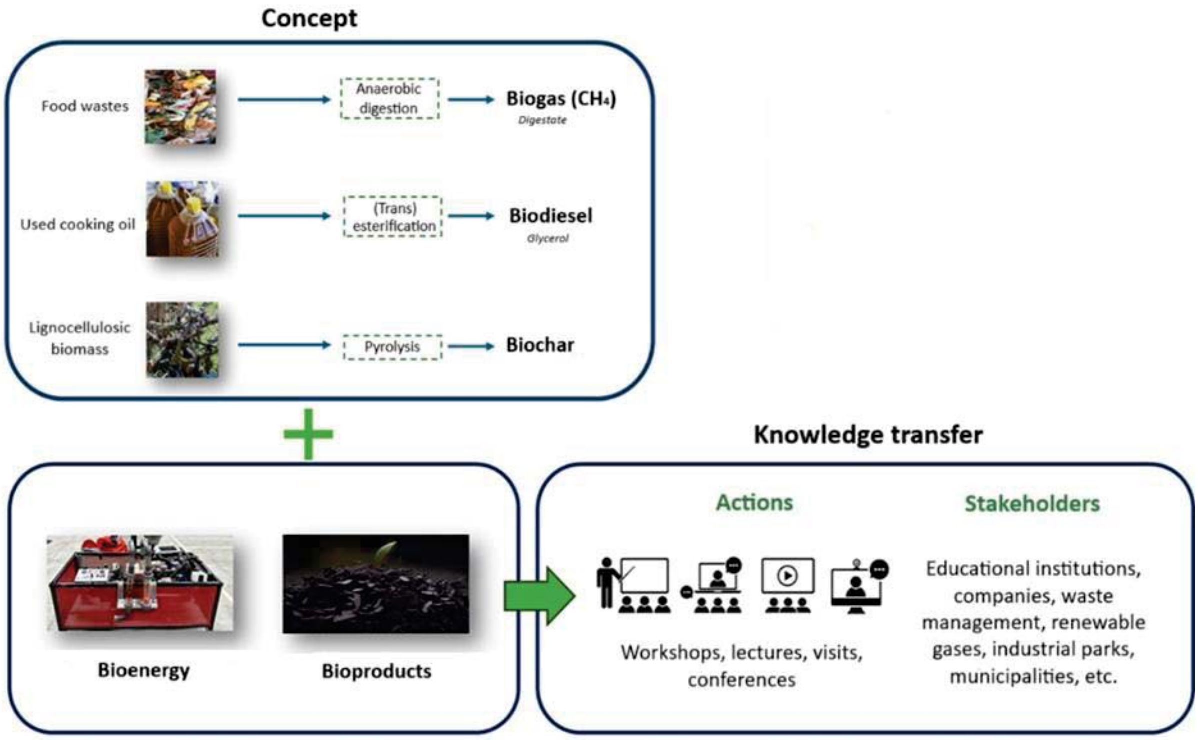

Figure 1. Process diagram for each technology and feedback loops among components.

Implementation considerations

The proposed framework aligns with material hierarchy principles: prioritizing material reuse (e.g., biochar as soil amendment), followed by bioenergy recovery (biogas, biodiesel) where material reuse is impractical.
Technical viability depends on feedstock availability and seasonal fluctuations in campus waste generation. Economic feasibility hinges on capital costs, product sales or use value, and avoided waste management expenditures. Social feasibility relies on stakeholder engagement, including students, staff, administrators, as well as regulatory frameworks and local partnerships. Pedagogical benefits include hands-on learning, research integration, and heightened environmental awareness. Potential challenges include process integration complexity, variable waste quality, regulatory compliance (e.g., fuel standards, biosolid regulations), and initial capital investment. Conversely, benefits include GHG reduction, energy independence, cost savings, skill development, and replicability in similar institutional settings.

DISCUSSION

The proposed integrated framework represents a novel application of CE principles within the context of UCs, with the potential to simultaneously address waste management, renewable energy production, environmental sustainability, and educational engagement. The combination of AD, (trans)esterification, and pyrolysis technologies is theoretically robust, offering synergistic interactions between processes and by-products, and aligning with current research in waste valorization and low-carbon transition systems.

Systems integration and synergy

From a systems perspective, the strength of this approach lies in its modular yet integrated design. Each technology targets a distinct waste stream commonly found on campuses (food waste, used cooking oils, and lignocellulosic biomass), while enabling interconnection among outputs and inputs. For example, the digestate from the AD process, traditionally considered a waste product requiring disposal, can be valorized further through pyrolysis to generate biochar. This biochar has demonstrated potential to improve AD process stability and methane yield when reintroduced into the digester [10][16], thereby creating a feedback-enhancing loop that increases both resource efficiency and process resilience.
Similarly, the glycerol generated from biodiesel production can be further valorized, either through anaerobic treatment or conversion into value-added compounds such as biopolymers or bioethanol [13]. Integrating such processes addresses one of the major criticisms of linear biodiesel production systems, which often neglect the complete valorization of co-products [17].
The pyrolysis step, beyond biochar, yields condensable vapors (bio-oil) and syngas. While the latter may be reinjected into the system for heat generation or electricity (e.g., in CHP units), bio-oil can be explored for refinement or as a precursor in chemical applications, though further treatment may be required to improve stability and energy density [14]. This triple-product configuration maximizes energy recovery and aligns with CE's principle of cascading material use. To operationalize the proposed modular and integrated waste valorization concept on a campus scale, a range of technical, infrastructural, and contextual elements must be considered. Despite its theoretical viability, practical implementation requires careful consideration of several constraints. Feedstock heterogeneity and seasonality, especially in academic settings with fluctuating population sizes during vacations, can impact system continuity and efficiency. Food waste volumes may be inconsistent, lignocellulosic inputs may require drying or pretreatment, and used cooking oil may vary in acidity and contaminant load, influencing biodiesel yield [21].
From the economic perspective, initial capital investments for installing AD units, pyrolysis reactors, and transesterification modules may be prohibitive for small institutions. However, modular and small-scale systems are increasingly available and may be deployed incrementally. Cost savings arise from reduced waste disposal fees, fossil energy displacement, and possible revenue from valorized products (e.g., biochar, digestate, biodiesel). Financial viability will depend on local market conditions, regulatory incentives, and integration with campus operations.
Table 1 summarizes the key requirements to support implementation.

Table 1. Key requirements to implement the proposed integrated campus waste valorization system.

Category	Requirements	Details
Technical feasibility	System integration plan, process parameters	Flows between AD, pyrolysis, and biodiesel; operating conditions (e.g., retention time, pyrolysis temperature, transesterification catalyst, etc.)
Feedstock characterization	Quantities, seasonality, and composition of available wastes	Campus-specific data for food waste, used cooking oil, and lignocellulosic biomass; elemental and proximate analyses, mineral composition, etc.
Product utilization pathways	End-uses and added-value applications for outputs	Biochar reuse in AD or soil; glycerol conversion (biopolymers, ethanol); bio-oil and syngas for energy generation or chemical precursors
Infrastructure & equipment	Existing vs. required infrastructure and pilot-scale technologies	Small-scale AD units, pyrolysis reactors, biodiesel processors; possible retrofitting of current lab setups
Environmental & economic assessment	Life Cycle (LCA) and Techno-Economic Analyses (TEA)	Resource efficiency, GHG reductions, CAPEX/OPEX, energy balance, sensitivity to feedstock variability
Policy & compliance	Regulatory framework and permitting	Waste-to-energy production on-site, emissions from pyrolysis, digestate land application, biodiesel handling
Stakeholder engagement	Involvement of key actors	Facilities management, campus sustainability teams, research units, and potential private sector collaborators

Furthermore, the proposed system aligns with national and European policies promoting CE, renewable energy, and decentralized waste management. It could be eligible for funding or recognition under sustainability accreditation schemes for UCs. Moreover, this model is highly replicable, particularly in semi-rural or peri-urban campuses where land availability, institutional autonomy, and community engagement are favorable.
Nevertheless, implementation must navigate existing regulatory constraints, especially regarding the classification and reuse of digestate and biochar, compliance with fuel standards for biodiesel, and safety protocols for high-temperature processes. Collaboration with local authorities, waste management agencies, and research partners will be essential.

Environmental and educational impact potential

By diverting waste from landfills and fossil-based energy sources, the system offers significant potential to reduce GHG emissions. Biogas and biodiesel, when produced from waste feedstocks, have well-documented lower life-cycle emissions compared to natural gas and petroleum diesel, respectively [18][19]. Furthermore, biochar has been increasingly recognized for its carbon sequestration potential, acting as a carbon-negative technology under certain conditions [20]. Applying biochar to soil may improve soil organic matter, water retention, and nutrient availability, offering co-benefits for experimental agricultural plots maintained by educational institutions.
In addition to environmental benefits, the system holds strong educational value. It enables multidisciplinary experiential learning in engineering, environmental sciences, chemistry, and sustainability studies. Students can be actively involved in waste audits, process optimization experiments, LCA, and TEA, thereby enhancing their practical and problem-solving skills.

This educational dimension contributes to long-term behavioral change and capacity building, which are crucial for CE mainstreaming.

CONCLUSIONS AND FUTURE WORK

The proposed model for integrated waste valorization in HEI campuses is technologically mature (in each of the separate technologies), but seldom implemented in combined, multi-stream configurations. Integration creates synergies: for example, biochar can improve AD performance and close agronomic loops, while biodiesel reduces fossil fuel dependence, and onsite biogas systems can provide heat and electricity with low distribution losses. Educational institutions are well-suited to pilot such systems due to their infrastructure, research capacity, and mission alignment.

Empirical studies, such as those at Cornell, FUTA, and Manchester, demonstrate partial successes. However, a fully integrated system across multiple waste types remains largely unexplored. This hypothesis offers a testable model for assessing closed-loop sustainability outcomes in rural or under-resourced higher education contexts.

This paper presents a hypothesis-based CE framework for campus waste valorization. By integrating three different waste valorization technologies, this concept seeks to create closed-loop resource cycles with educational and demonstrative value. Pilot implementation and evaluation, quantifying emissions reductions, economic performance, yield, and social acceptance, are the logical next steps. If validated, this framework may serve as a replicable blueprint for UCs worldwide committed to climate action and sustainable resource management.

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EVALUATION OF REFUSE-DERIVED FUEL GASIFICATION FOR ON-SITE ELECTRICITY GENERATION IN IRON ORE PROCESSING

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ABSTRACT

The industrial sector has shown significant interest in replacing traditional fossil fuels with alternative fuels derived from waste. This shift can reduce energy costs in production processes and minimize associated environmental impacts. However, municipal solid waste (MSW) presents challenges that hinder its use as an energy source. Its high moisture content, considerable heterogeneity, and the presence of inert components limit its higher heating value (HHV). In this context, the production of refuse-derived fuel (RDF) emerges as a promising strategy to enhance the fuel properties of MSW. RDF can serve as a primary energy source for energy-intensive industries, such as the iron and steel sector. Nevertheless, even with a more homogeneous and lower-moisture fuel, the direct combustion of RDF may result in the emission of harmful compounds and low energy conversion efficiencies. Thermochemical gasification, therefore, stands out as a technological alternative with considerable potential for generating thermal and electrical energy from RDF. It provides a more efficient and cleaner route for waste-to-energy conversion, particularly in iron production and related processes. This study aims to assess the technical feasibility of replacing grid electricity with electricity generated from RDF gasification in the iron production industry, while also exploring the recovery and reuse of by-products generated during the process. The main findings of the technical analysis show that the system can achieve a net electricity generation of 4,273.89 MWh, fully meeting the process demand. Additionally, 100 kg/h of char is recovered, which can substitute mineral coal in briquette production. The electrical efficiency of the system is 20.4%, and the overall energy efficiency reaches 27.4%.

KEYWORDS

Waste gasification, Electricity production, Sustainable pig-iron production, Industrial decarbonization.

1 INTRODUCTION

The demand for alternative fuels to gradually replace traditional fossil fuels has been increasing significantly in recent years, particularly in the industrial and transportation sectors, which are characterized by high energy demand and high greenhouse gas (GHG) emissions [1], [2]. The use of MSW in the context of "waste-to-energy" (WTE) presents several challenges that can hinder or prevent its effective recovery as an energy source in the industrial sector. One major issue is the high moisture content of MSW, which, combined with its highly heterogeneous nature and the presence of an inert fraction, often makes its direct use impractical. This is due to factors such as the significant energy required for water evaporation, the emissions of GHG and toxic substances, and the reduction of the HHV. Therefore, pretreatment is necessary to ensure that this waste meets the minimum specifications required for energy recovery [3].

In this context, the production of RDF serves as an effective strategy for creating an alternative fuel that can partially or fully replace traditional fossil fuels as the primary energy source in the industrial sector. RDF production has significant potential to enhance waste management practices by providing a sustainable alternative fuel while substantially decreasing the amount of waste directed to landfills [4]. The goal of the RDF production process is to increase the HHV, reduce moisture content, and improve homogeneity of the material. Additionally, specific pre-treatment methods for RDF, such as drying, grinding, pelletizing, and thermochemical treatments, can enhance the physical and chemical properties, leading to the production of an alternative fuel with improved combustion characteristics [5], [6].

Among the thermochemical methods for converting waste-derived fuels, gasification stands out due to its high potential for sustainable energy production and its effectiveness in reducing pollutant emissions such as NO_x and SO_x. Additionally, gasification of RDF minimizes the environmental impacts associated with landfilling and decreases the energy demand for traditional fossil fuels. This process generates a synthesis gas characterized by a high calorific value and low tar concentrations, along with a solid byproduct that has properties suitable for energy recovery or material reuse [7].

Han et al. studied the use of RDF chars from MSW as an alternative fuel in the iron industry. The authors found that incorporating up to 20% RDF coal with fossil fuels does not affect the quality of sintered ore. However, this blend increases CO and NO_x emissions while reducing SO_x emissions [8]. Similarly, Sharma et al. emphasize the benefits of RDF as an alternative fuel in energy-intensive industries. They report that using RDF in cement plants can reduce landfill waste by 30% and GHG emissions by 25%. Additionally, a 15-20% reduction in NO_x and SO_x emissions was observed with the incorporation of RDF in industrial furnaces [9].

This work aims to evaluate the gasification of RDF to produce electrical energy, thereby replacing traditional fossil fuels and contributing to the gradual reduction of the carbon footprint in the iron and steel industry.

2 MATERIALS AND METHODS

This study evaluates the replacement of electricity from the grid, currently used in iron ore processing in induction furnaces, with electricity generated through the bubbling fluidised bed gasification of RDF. This process involves cleaning and conditioning of the produced syngas, followed by power generation using internal combustion engines adapted to operate on syngas and coupled to synchronous generators. The process flow diagram for iron beneficiation using RDF derived from MSW for electricity generation via gasification is shown in Figure 1.

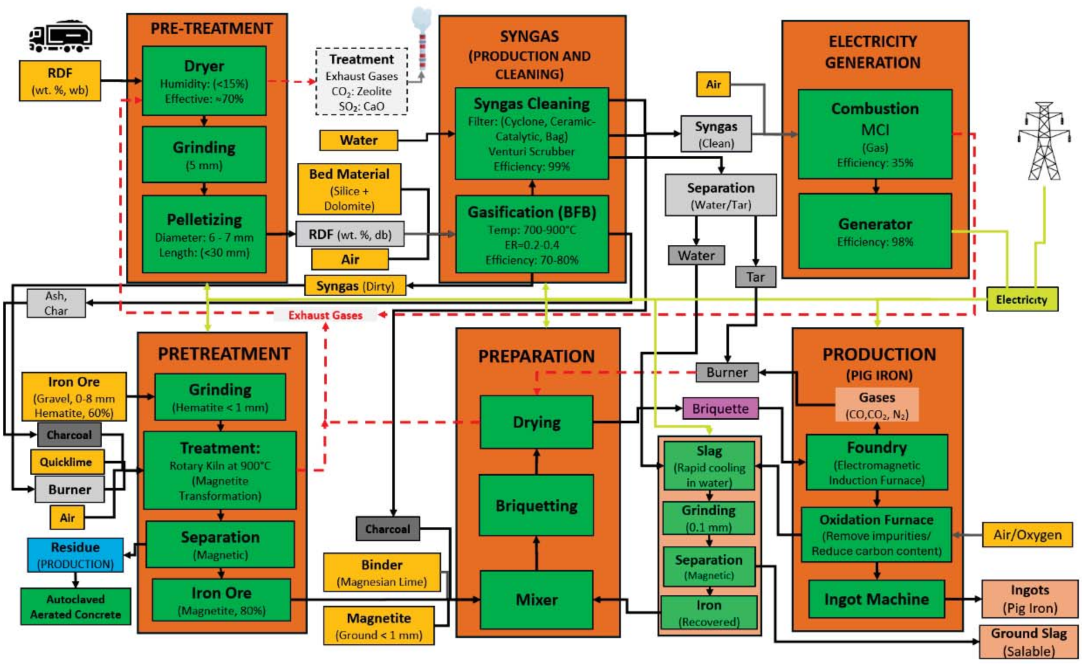

Figure 1. Flow diagram of the iron beneficiation process with electricity generation via RDF gasification in ICE-G system.

The analysis is based on average hourly electricity and coal consumption data to produce 4.2 t/h of iron. The electromagnetic induction furnace comprises two interchangeable crucibles and operates in 40.5-minute cycles. Each cycle processes 5 tonnes of briquetted iron ore and consumes 2.5 MWh of electricity. Operating 12 hours daily, it can process 87.1 tonnes of briquettes, yielding 50.2 tonnes of pig iron, 17.9 tonnes of slag, and 19 tonnes of gases (mainly CO and CO_2). Daily electricity consumption is 48.8 MWh, of which 44.4 MWh is for the furnace and 4.4 MWh for other plant components such as mills, briquetting machines, and electric motors.

Based on this information, the electricity generation system was designed, comprising a gasification unit (a bubbling fluidized bed reactor and a wet gas cleaning system) and a generation unit (an internal combustion engine coupled to a synchronous generator). RDF is used as a feedstock, with its properties characterized in prior studies evaluating its suitability as a fuel, referenced throughout this work. Considering a lower heating value (LHV) of 17.6 MJ/kg and moisture content of 11.8%, as reported in Table 1, the daily fuel demand can be estimated.

Table 1. Characterization of RDF [10].

Proximate analysis (wt.%, wet basis)	
Moisture*	11.8
Volatile matter	85.6
Fixed carbon	4.2
Ash	10.7
Ultimate analysis (wt.%, dry basis)	
C	53.7
H	8.7
N	1.5
S	n.d.**
O *(by difference)*	36.1
LHV *(MJ/kg, dry basis)*	17.6

** Moisture after dryer. ** Not determined, below the detection limit of the method, 100 ppm wt.*

The proposed system consists of several stages. RDF may undergo pre-treatment to meet gasification requirements and is then converted into syngas in an atmospheric bubbling fluidized bed reactor using air as the gasifying agent. The syngas then goes through a multistage wet cleaning system to remove impurities such as unconverted carbon, particulates, and tars. This system includes a dry cyclonic filter, a Venturi-Schreiber-type scrubber, passive filters (sand, sawdust, activated carbon), and a final bag filter. A portion of the syngas is used to fuel a rotary kiln for thermal pre-treatment of iron ore; the rest is directed to ICE-G units for electricity generation.

Carbon recovered from the cyclonic filter replaces mineral coal in the production of iron briquettes. Briquettes consist of 63% magnetite, 29% limestone, and 8% carbon, with a dolomitic lime binder. Tars separated from scrubber water are burned with off-gases from the induction furnace to provide heat for briquette drying. Scrubber water is reused to quickly cool furnace slag, forming amorphous structures suitable as cement additives. This prevents crystallization, creates air bubbles, and reduces slag density—ideal for producing high-strength cements known for durability, corrosion resistance, and lower environmental impact.

Ashes from gasification are mixed with iron ore gravel (<8 mm) and quicklime, ground to <1 mm, and thermally treated at ~900 °C to convert hematite into magnetite and remove impurities like phosphorus, common in Portuguese iron ore. Magnetic separation yields a concentrate of up to 80% magnetite. Residuals are used to produce autoclaved aerated concrete (AAC), a lightweight, prefabricated construction material with excellent thermal and acoustic insulation properties. With densities from 300 to 800 kg/m³, AAC is easy to transport, fire- and water-resistant.

Energy Analysis

For the energy analysis, a theoretical model was developed based on the principles of mass and energy conservation, enabling the characterisation of the energy system configuration. The energy balance applied to the gasification system is described by equations (1–6).

The cold gas thermal efficiency of the gasification process, the electrical generation efficiency, and the overall system efficiency are calculated using expressions (7–9), assuming a cold gas efficiency of 75% for air-based gasification [11], a mechanical efficiency of 30% for the internal combustion engine–generator set (ICE-G) [12], and a thermal efficiency of 80% for the rotary kiln [13], [14]. Table 2 summarizes the equations for energy analysis.

Table 2. Summary of equations for energy analysis.

Nº	Equation	Description
1	$\dot{E}_{RDF} = \dot{E}_{Syngas} + \dot{E}_{Tar} + \dot{E}_{ash} + Q_G$	Energy balance for gasification system
2	$\dot{E}_{RDF} = \dot{m}_{RDF} LHV_{RDF}$	Energy from RDF
5	$\dot{E}_{Syngas} = \dot{m}_{Syngas} \cdot \left(Cp \times \Delta T + LHV_{Syngas}\right)$	Energy from syngas
4	$\dot{E}_{Tar} = \dot{m}_{Tar} \times (Cp \times \Delta T + LHV_{Tar})$	Energy from tar
5	$\dot{E}_{Ash} = \dot{m}_{ash} \times Cp \times \Delta T$	Energy from ash
6	$\eta_{coldgas} = \frac{\dot{E}_{Syngas}}{\dot{E}_{RDF}}$	Cold gasifier efficiency
7	$\eta_{Ther.} = \frac{(\dot{E}_{Syngas} \cdot \eta_{Burer})}{\dot{E}_{RDF}}$	Thermal efficiency
8	$\eta_{Elect.} = \frac{(\dot{E}_{Syngas} \cdot \eta_{ICE-G})}{\dot{E}_{RDF}}$	Electrical efficiency
9	$\eta_{Global} = \frac{(\dot{E}_{Elect.} \cdot \dot{E}_{Ther.})}{\dot{E}_{RDF}}$	Global efficiency

3 RESULTS AND DISCUSSION

The main energy performance indicators for integrating RDF gasification into the pig iron production industry, as shown in the system configuration of Figure 1, are summarized in Table 3.

Table 3. Main technical and environmental performance indexes.

Parameter	Case
Biomass input (t/h)	5.78
Biomass LHV (MJ/kg)	17.60
Biomass thermal input (MW_{th})	20.9
Syngas output (t/h)	12.7
Syngas LHV (MJ/kg)	5.1
Syngas thermal output (MWth)	15.7
Electricity Production (MWe)	4.3
Electricity Consumed EIF (MWe)	3.7
Electricity Consumed Others (MWe)	0.6
Thermal Energy (MWth)	1.1
Electrical Efficiency (%)	20.4
Global Efficiency (%)	27.3

Figure 2 presents the Sankey diagram illustrating the system's energy flows. For clarity, only the main flows are included, specifically those related to the RDF gasification unit, the electricity generation system using ICE-G, and the rotary kiln.

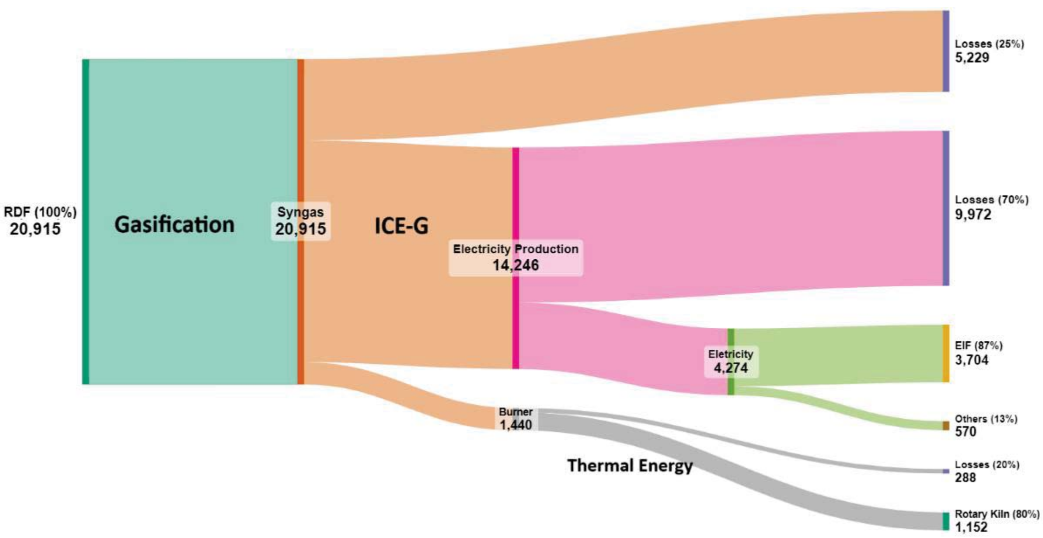

Figure 2. Sankey diagram of the main energy flows.

During gasification, the energy contained in the RDF is converted into thermal and chemical energy in the form of syngas. Heat losses and solid residues (ash and unconverted carbon) account for approximately 25% of the total energy losses (see Figure 2). Notably, the unconverted carbon is recovered and reused as an additive in the production of iron ore briquettes, replacing mineral coal.

The system under analysis requires a gasification unit with a thermal capacity of 20.51 MW_{th}, equivalent to an annual feedstock demand exceeding 16,864 tonnes. To achieve this, a drying unit (if required) with a processing capacity of 5.8 t/h is needed to reduce the RDF's moisture content from 40% to 11%. The dried RDF is processed in a gasification plant comprising two BFB gasifiers, each with a thermal capacity of 12 MW. This system, specifically the ANDRITZ BFB gasifier, is designed for RDF gasification and includes a total thermal capacity of 24 MW and a wet syngas cleaning system [15].

The system generates 12.7 t/h of syngas, of which 11.0 t/h are used in ICE-G units to produce 4.3 MW of electricity. Energy losses in this stage reach approximately 70% (see Figure 2), primarily due to the thermal energy carried by the exhaust gases. The remaining 1.3 t/h of syngas is combusted to supply the thermal energy required for iron ore pretreatment, where hematite is converted into magnetite (80% Fe), resulting in additional losses of about 20.4%. The overall system efficiency—considering both thermal and electrical outputs—is estimated at 25.9%.

As clearly illustrated in the Sankey diagram in Figure 2, the highest thermal losses in the system occur in the ICE-G unit, which converts only 30% of the primary energy it receives into useful electricity. A potential strategy to reduce these losses is the implementation of a cogeneration system, which would produce both electricity and hot/chilled water, thereby improving the overall system efficiency. The gasification unit also exhibits substantial thermal losses, estimated at approximately 25%. Strategies to reduce these losses include recovering residual thermal energy from the syngas and employing alternative gasifying agents such as oxygen, steam, or their mixtures.

4 CONCLUSIONS

This study presents a technical assessment of replacing grid electricity, currently used in iron ore processing via electromagnetic induction furnaces, with electricity generated from RDF gasification using ICE-G systems.

The analysis demonstrates that this approach is technically viable, enabling the complete substitution of grid electricity with electricity generated on-site through RDF gasification. Under the evaluated conditions, the system achieved an electrical output of 4.3 MWh and an additional thermal output of 1.1 MWh, with an annual RDF consumption of approximately 16,864.2 t/year. The electrical efficiency of the system is estimated at 20.4%, while the overall energy efficiency reaches 27.3%.

These findings underscore the strategic potential of biomass and waste gasification technologies as sustainable energy solutions for energy-intensive industries, such as mining, which have traditionally relied on fossil fuels. Integrating such technologies can play a crucial role in supporting industrial decarbonization efforts and advancing the transition toward a circular bioeconomy.

Finally, it is essential to emphasise that the successful implementation of these solutions will also depend on the development of appropriate public policies and economic instruments that promote the adoption of clean technologies in industrial processes.

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The Difference Between Social Innovation and Social Technology: A View from Scientific Literature.

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ABSTRACT

The concepts of Social Technology (ST) and Social Innovation (SI) are becoming increasingly widespread across various sectors. Considering that the idea of SI is inseparable from that of ST, the connection between them is a growing field of study of extreme relevance to society. This research aims to analyze the relationship between these two concepts. The methodology adopted is qualitative and, based on the technical procedures used, is a documentary study. The research brings together the main definitions adopted for social technology and social innovation and describes the methodological approach used in collecting articles and documentary data. As a result, it identifies what characterizes each concept, details the relationship between them, presents seven differentiating parameters, possible movements of change, and four relevant processes connected to social technology that can trigger social innovation.

KEYWORDS
Innovation, Social Innovation, Social Technology, Literature Review

INTRODUCTION

The concepts of Social Technology (ST) and Social Innovation (SI) are becoming increasingly widespread across various sectors (public, private, third sector, and nonprofit organizations) in the face of complex global issues such as: scarcity of natural resources, climate change, ecological catastrophes, food instability and insecurity, social inequality, epidemics, the struggle for social rights, and the search for new, more sustainable and communal ways of life and coexistence.

The two concepts are closely linked, but they do not represent the same thing. The difference between them can be understood as distinct moments within the same flow (NASCIMENTO, 2021). Social technologies can be drivers of social innovations, but this does not necessarily occur in all situations. The reverse is also possible, with some social innovations generating new social technologies (DE MEDEIROS et al., 2017).

There is a gap in the literature regarding studies that seek to understand and analyze the relationship between ST and SI. The studies found are still scarce and recent. Therefore, it is a growing field of study, considered vital because it is seen as an alternative for developing public policies and a path toward creating more sustainable systems and meeting the goals set by the United Nations (UN) in the 2030 Agenda.

This research aims to analyze, through literature, the relationship between these two concepts. However, there are still a few studies on the different elements of the SI process and on which processes generate the most significant influence on the creation of economic, social, and sustainable value (FOROUDI, 2021). Furthermore, a study (DOROTEU; CARVALHO; DOS SANTOS, 2018) found that the Brazilian government still neglects the promotion of social technologies.

THEORETICAL FRAMEWORK

The term social technology (ST) emerged from the contradiction of technological advancement, which simultaneously brought improvements but also diminished the quality of life of the masses. Conventional Technology (CT) produced in academia, or within laboratories, considered other technologies to be "second-class technologies" (THOMAS, 2009). According to Dagnino (2019), this disqualification of popular knowledge as non-scientific is one of the consequences of the separation between science and technology "invented" by capitalism. Due to the disastrous aspects arising from the CT development processes, discussions began to emerge about alternative technologies to conventional ones, such as Democratic, Appropriate, and Alternative Technologies. These discussions led to the concept of TS (THOMAS, 2009).

The origins of ST can be understood as stemming from the Appropriate Technology (AT) movement of the late 19th century. Between 1924 and 1927, Gandhi developed the first AT, which was not yet termed as such, but the same concept was used, called Charkha. At that time, Gandhi already advocated for the protagonism and empowerment of villagers throughout the technological development process, stating: "Production by the masses, not mass production" (DAGNINO; BRANDÃO; NOVAES, 2004). Since then, networks and movements of technologies called "appropriate," "intermediate," "grassroots," "alternative," "community," "environmentally appropriate," "clean," "popular," "humane," "ecological," "social," etc., have begun to proliferate. There are many expressions, each emphasizing specificity, but all of them somehow differ from conventional technologies by not aiming for large-scale production and intensive use of capital. These technologies have characteristics such as community participation throughout the process, the low cost of products and services, the investment required to produce them, simplicity, and positive effects on the quality of life of the community and the environment (DAGNINO; BRANDÃO; NOVAES, 2004). TS emerged in Brazil in the 1980s motivated by the effort to overcome the limitations of appropriate technology, adapting to the context of Latin American countries, being guided by the needs of users, rehabilitating and developing traditional technologies used in each social context and aiming at adaptation to the environment and social inclusion (DAGNINO; BRANDÃO; NOVAES, 2004; DE ALBUQUERQUE, 2009; POZZEBON, 2015).

More recently, the terms "solidarity technology" and "solidarity technoscience" have been considered. "Technoscience" is used because it is inconvenient to separate science from technology, and "solidarity" is used because of ST's close relationship with the concept of the

Solidarity Economy. Furthermore, these technologies are derived from the informal sector and seek to address social exclusion based on collective ownership of the means of production and self-management (DAGNINO, 2019; NASCIMENTO; BINOTTO; BENINI, 2019).

Dagnino (2019) defines solidarity technoscience as: "how knowledge should be generated and used in the production and consumption of goods and services in solidarity networks, respecting their values (collective ownership and self-management) to meet collective needs." He understands that we can call it social technology, but always understands that it is a technoscience, since it is impossible to separate science from technology. Each community, or each specific social context, has its characteristics, needs, and culture. Therefore, technologies must be developed in conjunction with communities, maintaining and strengthening existing social and intercultural relationships and always seeking to democratize the technological process (ADDOR, 2020). This is why the concept of reapplication, not replication, is used. When a solution is implemented in locations other than the one in which it was developed, the social technology will necessarily be recreated, adapted to the new reality, and new values and meanings will be added, as each context will always be unique. Reapplication, therefore, is an action open to the latest (THOMAS, 2009). When it comes to social technology, in addition to being open to the new, it must also be open to the people.

In summary, in the literature, we find that the definition of social technology is still not a consensus, and what characterizes the field of social technology is not the product but the process. Using it in the plural (social technologies) can limit it to a set of technological practices rather than a theoretical-methodological field (ADDOR, 2020; DE VASCONCELLOS, 2025). The philosopher Martin Heidegger (1977) stated that the essence of technology is not the artifacts, techniques, procedures, methodologies, and processes we create, but how it reveals itself and shapes our understanding of the world.

METHODOLOGY

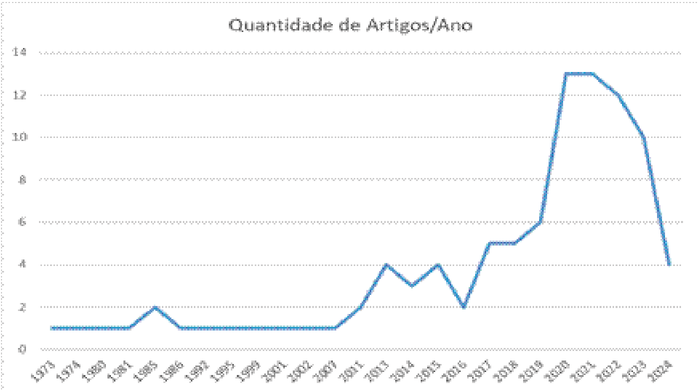
This research is qualitative and, based on the technical procedures used, is a documentary study. An initial search of the CAPES journal portal using the terms "social innovation" and "social technology" was conducted on July 15, 2023, yielding 54 results. After removing duplicates, 39 articles remained, the abstracts of which were read. Those with titles closer to the research topic were read in full. A second search was subsequently conducted in the Science Direct, Scielo, and Scopus databases on April 29, 2024, to gain a deeper understanding of existing research on the subject. The following search formula was used: ("social technology" AND "social innovation") OR ("social innovation" AND "social technology"). After removing duplicates, 96 articles remained. Of these, 37 were read in full, as the title indicated they best fit the research topic. We sought to separate the 20 most cited and the most cited over the last five years. This initial analysis revealed a gap in the literature regarding studies that analyze the relationship between social technology and social innovation.

RESULTS

The term "social technology" to define social innovation initiatives (or initiatives that can trigger social innovations) is most commonly used in the Brazilian context. International references (ABHARI et al., 2023; TARIK; WAFIA; SOFIANE, 2021; SKARŽAUSKAITĖ, 2012) cite the term "social technology" as internet-based tools to improve "social" aspects.

Figure 3 shows the number of articles published per year. It can be seen that over 90% of the articles were published after 2017, demonstrating that studies seeking to understand and analyze the relationship between social technologies and social innovations are still scarce and recent, demonstrating the need for more research in this area.

Figure 3 – Number of articles published per year



Source: authors (2024)

Some studies relate the concepts of social technology and social innovation by developing conceptual and operational frameworks (POZZEBON; TELLO-ROZAS; HECK, 2021; SOUZA; POZZEBON, 2020; DE MEDEIROS et al., 2017). They identify the operating mechanisms and modes of action of social technology and confirm that it helps promote social transformation. Others (DE MEDEIROS; GÓMEZ, 2019; JOSHI; YENNETI, 2020) analyze the expansion of social technology implementation through case studies.

Most articles are empirical case studies of implemented social technologies, such as the implementation of a living lab in Japan to maintain and improve a healthy diet during the COVID-19 pandemic (TABATA et al., 2022); the production of solar cookers in an Argentine province (SEOANE et al., 2013); and the Mandalla Project, in northeastern Brazil, which uses irrigated agriculture and an agro-industrial production system to raise small animals using natural methods (SOUZA COSTA et al., 2013). Many of the articles discuss the importance of involving the community in all stages of the project and the importance of empathy and the strengthening of human relationships in the social innovation process (DANA, 2021; VAN DER BIJL-BROUWER; MALCOLM, 2020). There are articles on so-called grassroots and/or community innovations, which are ideas that emerged from the communities themselves and are led by them, which can also be called "bottom-up" social innovations (DANA, 2021; JONES, 2021; AGUIRRE-BASTOS; WEBER, 2018; DE FÁTIMA FERREIRO, 2023). Others have a vision more focused on enterprise social networks (ABHARI, 2021), business and management (REBEHY, 2017), Industry 5.0 (DWIVEDI, 2023; LENG, 2022), smart cities (ANDREANI, 2019) and Artificial Intelligence (PAN; NISHANT, 2023; XIA; SEMIRUMI; REZAEI, 2023). Therefore, the term "social technology" to describe political processes of sociotechnical constructions, which seek a new way of addressing the relationship between technoscience and society, was developed by South American researchers and practitioners. It is suggested that it be used in Portuguese, without translation, to reinforce its historical trajectory of struggle by existing intellectual social movements, from which European and North American researchers have an excellent opportunity to learn (POZZEBON, 2015; DE VASCONCELLOS, 2025).

There is a close connection between the concepts of ST and SI, and they are inseparable. That is, social technologies drive social innovations, while the latter also give rise to the former (DE MEDEIROS et al., 2017). Therefore, ST is considered a potential tool for SI (DE MEDEIROS et al., 2017; TARIK; WAFIA; SOFIANE, 2021). Both concepts have a dimension of resistance to capitalist logic (NASCIMENTO, 2021), breaking with individualism and producing what Manzini (2023) calls systemic discontinuity in a countertrend movement.

A recent literature review on the concept of social technology (DE VASCONCELLOS, 2025) showed that social innovation is also used in literature as a synonym for social technology, which can weaken political processes in practice. However, there are differences between the concepts, as illustrated in Figure 4, which are: geographic origin, historical trajectory, types of knowledge, levels, focus, primary process involved, and value created. The concept of SI was initially developed by Canadian researchers at the Centre de Recherche sur l'Innovation (Crises) research center at the University of Quebec. The idea of social innovation, as we have seen, is ancient, but its widespread dissemination began in the 2000s (NASCIMENTO, 2021; POZZEBON; TELLO-ROZAS; HECK, 2021). The concept of ST emerged at the end of the 20th century, as discussed earlier in this work.

Another difference between the concepts lies in the types of knowledge. SI refers primarily to intangible/immaterial knowledge, while ST refers to applied knowledge, which can be tangible or intangible—two aspects of the same continuum.

SI is a local community initiative that first seeks the knowledge necessary to meet the perceived needs of these communities and then applies this knowledge collectively. This application refers to ST, and when absorbed and expanded to other locations/communities, along with interactions with other actors and social sectors, it generates a transformation in the culture and daily lives of citizens, resulting in social innovation (DAGNINO; GOMES, 2000; NASCIMENTO, 2021). The social transformation brought about by a social technology is local (micro-level). When it expands and adapts to other contexts, it can trigger more systemic changes (meso- and macro-level), leading to more significant social transformations for society. This change refers to SI. Therefore, social technology can also be understood as one of the pillars that support the flow of social innovation (DE MEDEIROS et al., 2017).

The adoption of social technologies by the community, their use on a larger scale, and collaborative work with other sectors mean that the developed social technologies can trigger social innovations. It is clear that local change can trigger larger movements: such as changes in the social context, the creation of new social practices, and new social systems that are more collaborative (MANZINI, 2008), regenerative (WAHL, 2020), and transformative (HAXELTINE, 2016).

A study conducted with Embrapa (Brazilian Agricultural Research Corporation) analyzed two social innovation projects and demonstrated that, just as local change can trigger larger, more systemic movements, the reverse is also true: more systemic movements and actions can help promote local change. For example, local movements can generate broader public policies, and more systemic movements can support generations of local mobilizations (MOURA; BRAGA, 2025).

It can be observed that at least four processes connected to social technologies are highly relevant for them to trigger social innovations: collaborative mediation, access to ST, cooperative networks, and connections of affection. The role of the mediator is vital for technology to gain social adoption and expand. The mediator is someone from the community who has a connection with the local people and will perform an "educational role" for the population, presenting the new ST, how to use it, how the process will work, and its benefits. This mediation is not a simple interaction with the community; it is a collaborative interaction, that is, it contributes to the development of a collective community consciousness, generating new ways of being well in that context, more sustainable ways of living—hence the term "collaborative mediation." A ST must be sustainable, accessible, and understandable to all. That is, it must prioritize the resources available locally and utilize them. Furthermore, it must be easy for the community to understand and use. The community must appropriate the technology and know-how to maintain it regularly, always reconciling traditional knowledge with advances in science and technology.

CONCLUSION

There is a gap in the literature regarding studies that seek to understand and analyze the relationship between social technology and social innovation. The studies found are still scarce and recent. Therefore, this work aims to contribute to this field, which, as seen in this research, is growing.

Consistent with the research objective, the analysis of the relationship between the concepts of ST and SI generated some insights and conclusions. The research identified the characteristics of each concept, their similarities, their differences, possible movements for change, and four processes connected to social technology that can trigger social innovation.

First, it is clear from the literature that both concepts still lack a consensus regarding their definition. It can be understood that what characterizes the field of social technology is its process: replicable techniques and/or methodologies, developed in solidarity networks together with the community and appropriated by it, collectively owned and in the public domain, which represent effective solutions for social transformations, strengthening existing social and intercultural relations and always seeking the democratization of the technological process (ITS, 2004; DAGNINO, 2019; ADDOR, 2020; FBB, 2023).

The field of social innovation is characterized by being an intangible phenomenon, that is, it manifests itself in changes in attitudes, behaviors, and perceptions of social groups, generally emerging through "bottom-up" rather than "top-down" organizational processes. Social innovation represents a new solution to a social problem that is more effective, efficient, sustainable, fair, and absorbed by society, creating new social relationships or collaborations and increasing society's capacity for action (MURRAY; CAULIER-GRICE; MULGAN, 2010; CAJAÍBA-SANTANA, 2014; MANZINI, 2008; PHILLS; DEIGLMEIER; MILLER, 2008).

These concepts are inseparable from each other. Social technologies drive social innovations, while the latter also give rise to the former (DE MEDEIROS et al., 2017). Therefore, ST is considered a potential tool for SI (DE MEDEIROS et al., 2017; TARIK; WAFIA; SOFIANE, 2021). Both possess a dimension of resistance to capitalist logic (NASCIMENTO, 2021), breaking with individualism and producing a systemic discontinuity in a countertrend movement (MANZINI, 2023).

The differences between the concepts lie in their geographic origin, their historical trajectory, the types of knowledge generated, the levels of social reach, their focus, the primary process involved, and the value created. It was also observed that changes can be from the local to the systemic or from the systemic to the regional. Local movements can generate broader public policies, and more systemic movements can support generations of local mobilizations (MOURA; BRAGA, 2025).

Finally, because of this research, it was also observed that at least four processes connected to social technologies are highly relevant for them to trigger social innovations: collaborative mediation, access to ST, cooperative networks, and connections of affection. A ST can be triggered by an SI when all these processes are met. The social dimension represents not only overcoming the social needs faced by the community served, but also the empowerment of the actors involved, inclusion, interaction with the community throughout the development process, and the change in attitudes, behaviors, and perceptions, generating a new social practice, a new culture, creating ways of living well in the world through sustainable, community-based, and collaborative practices.

Besides the social dimension, it must contain something new, be new to the context in which it is inserted, and be an improved, more effective, efficient, sustainable, or fair idea. Finally, they must be more than just ideas; they must be implemented, absorbed, and expanded by society, generating value for society as a whole and not just for private individuals.

This study has limitations in the literature reviewed and the construction of the theoretical framework, and lacks empirical analysis. Suggestions for future studies include deepening empirical analyses in cases of ST that may or may not have the potential to trigger social innovations, further research on the essential elements in the SI process, and the construction of possible tools for measuring the degrees of development of ST and SI. It is also crucial to monitor the direction in which it is heading, to confirm such potential and thus avoid reinforcing patterns of exclusion and power asymmetry.

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SYSTEMATIC REVIEW AND BIBLIOMETRIC ANALYSIS OF ELECTRIC VEHICLE ADOPTION IN BRAZIL

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ABSTRACT

This study investigates the adoption of electric vehicles (EVs) in Brazil through a combined bibliometric and systematic review approach. The research aims to identify key themes, scientific trends, and critical barriers that influence the expansion of electromobility in the national context. A total of 30 articles were retrieved from the Scopus database using a defined search string, with 10 studies selected for in-depth analysis. Bibliometric analysis, performed using VOSviewer, identified five thematic clusters: electric vehicle technology, Brazil, sustainability, charging infrastructure, and consumer behavior. The systematic review, following the PRISMA protocol, revealed recurring challenges such as high acquisition costs, limited recharging infrastructure, and lack of economic incentives. On the other hand, opportunities were identified based on the country's renewable energy matrix and growing environmental awareness. Despite the use of a single database and the absence of indexed keywords in some articles, the convergence between bibliometric and qualitative findings reinforces the consistency of the results. This paper contributes to the academic debate by mapping the state of scientific knowledge on EV adoption in Brazil and providing recommendations for researchers and policymakers to support the transition to sustainable mobility.

KEYWORDS

Electric Vehicles, Electromobility, Bibliometric Analysis, PRISMA, Brazil, Sustainable Transportation.

INTRODUCTION

Sustainable urban mobility is central to discussions on energy transition and climate change mitigation. The Brazilian transportation system remains dominated by individual road transport, accounting for around 64% of passenger mobility, according to the Ten-Year Energy Expansion Plan 2034 by EPE [2]. In addition to being a significant source of emissions, the sector is one of the largest energy consumers and plays a strategic role in economic growth, as the movement of goods and people drives value generation.

One common drawback of the transportation sector is a greenhouse gas emission in Brazil, responsible for approximately 223.8 million tons for CO_2 (major source of greenhouse emissions) in 2023 [1], highlighting the urgent need to adopt clean technologies and sustainable energy alternatives, such as electric vehicles, to meet climate targets.

Recently, the energy transition has driven significant transformations in the automotive sector, especially in urban mobility, fostering technological changes towards sustainability. Recent studies highlight electric vehicles (EVs) as a key alternative to reduce emissions and fossil fuels dependence, fostering more sustainable cities [3].

Within this framework, Brazil has experienced marked progress in expanding the electrified fleet and charging infrastructure. According to the Brazilian Electric Vehicle Association [4], 177,358 light electrified vehicles were registered in 2024 – an 89% increase from 93,927 in 2023. By February 2025, there were 14,827 charging stations in 1,363 municipalities, underscoring the considerable expansion of the national charging network. However, this represents less than 25% of the country's 5,570 municipalities [18], revealing a limited geographic reach and a structural barrier to the large-scale EV adoption outside major urban centers.

Despite progress, the effective insertion of electrified vehicles into the national market still faces major challenges. In 2024, only 7.1% of the 2,487,536 light vehicles registered in Brazil were electrified – including battery electric vehicles (BEV), hybrid electric vehicles (HEV), and plug-in hybrid electric vehicles (PHEV) [5]. This limited market share highlights the need for stronger policies, incentives, and strategies to address structural, economic, and cultural barriers. Several studies reviewed in this paper explore these issues and opportunities for advancing electromobility in Brazil.

Studies by [6] also indicate that transport demand remains strongly linked to Gross Domestic Product (GDP) growth, projected at 2.8% per year from 2024 to 2034. Sectoral energy consumption is driven by rising per capita GDP, logistics expansion, environmental policy, shifting consumption habits, connectivity, and new technologies [6]. These elements increase demand for freight and passenger transport, while challenging the adoption of energy-efficient and environmentally sustainable solutions.

The predominance of individual motorized transport in Brazil is closely linked to the country's dispersed urbanization pattern, the rapid growth of the private automobile fleet over the past two decades, and a historical lack of investment in public transport infrastructure. Barriers to transport electrification persist despite Brazil's clean electricity mix, including geographic concentration of charging infrastructure, high EV costs, lack of consistent tax incentives, and limited domestic battery and component production [6].

The importance of this study lies in its effort to bridge a significant gap in the literature by integrating behavioral aspects—such as consumer perception, purchase intention, and user readiness—into the discussion on electric vehicle (EV) adoption in Brazil. While technical and regulatory barriers are frequently addressed in previous works, the role of consumer behavior remains underexplored, especially in large-scale literature analyses. This study responds to this gap by combining bibliometric mapping with a systematic literature review to examine how recent research (2020–2025) addresses behavioral drivers in the Brazilian context, revealing how individual-level factors intersect with structural challenges such as cost, infrastructure, and public policy.

To achieve this, the study applies the PRISMA protocol (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) for the systematic review, alongside a bibliometric analysis using VOSviewer software. As highlighted by [7], systematic reviews aim to clarify the research process by making the selection and filtering of information transparent and reproducible. Although the primary focus is on national EV adoption, the inclusion of behavioral dimensions adds a critical layer to the investigation. This integrated methodological approach allows for the identification of scientific trends and gaps while supporting evidence-based decision-making to accelerate sustainable mobility in Brazil.

1. Materials and Methods

This study is based on scientific articles retrieved from the Scopus database using the search string: TITLE-ABS-KEY (("electric vehicle" OR "e-mobility" OR "electromobility") AND ("Brazil" OR "Brasil") AND ("consumer")).

Scopus was chosen for its extensive coverage in energy, transport, and sustainability research. The search, conducted in July 2025, returned 30 documents. After applying filters—publication year (2020–2025), language (English), and country (Brazil)—19 articles remained. From these, the 10 most relevant (based on Scopus relevance ranking) were selected for in-depth analysis.

The methodological approach combines a systematic review following the PRISMA protocol and a bibliometric analysis using VOSviewer, allowing the identification of research trends, knowledge gaps, and key contributors to the debate on EV adoption in Brazil.

1.1 Bibliometric Review

The bibliometric analysis was carried out using the VOSviewer software, which enables the visualization of bibliographic networks based on data exported from the Scopus database. The analysis considered the 30 articles initially retrieved by the search string, before the application of language, date, and country filters, as this broader dataset provides a more comprehensive view of the scientific production related to the topic.

The bibliometric review aimed to identify the intellectual, social, and conceptual structure of the scientific output on the insertion of electric vehicles in Brazil. The analysis included keyword co-occurrence, co-authorship networks, and thematic clusters to map the evolution and concentration of research in this field.

For the construction of the keyword co-occurrence network, author keywords were used, with a minimum threshold of 2 occurrences per term. This approach enabled the identification of central terms such as “electric vehicle”, “Brazil”, “sustainability”, “charging infrastructure”, and “consumer behavior”, which reflect the main themes addressed in the literature.

The generated bibliometric map also revealed interdisciplinary connections between topics related to energy, transportation, innovation, public policies, and user perception. The visualization of clusters made it possible to identify different research lines, including those focused on technological aspects, environmental impacts, economic evaluation, and policy incentives for electromobility.

This bibliometric mapping contributes to a better understanding of the current state of scientific research on electric vehicles in Brazil and provides valuable insights into emerging topics and research opportunities in this area.

1.2 Systematic Review

Complementing the bibliometric analysis, a systematic review was conducted to qualitatively examine the most relevant studies and identify research gaps on EV adoption in Brazil. Following the PRISMA protocol, the process ensured transparency and reproducibility.

As shown in Figure 1, 30 articles were initially retrieved from Scopus. After applying filters (years 2020–2025, English language, and focus on Brazil), 19 remained. From these, 10 key studies were selected based on relevance and full-text availability.

- The review addressed four guiding questions:
- What is the current scenario of EV adoption in Brazil?
- What public policies, incentives, and regulations are highlighted?
- What are the main barriers and opportunities for electromobility?
- How is consumer perception treated, and how does it influence adoption?

These guiding questions enabled a deeper understanding of the scientific discourse on electromobility in Brazil, complementing the quantitative insights obtained through bibliometric indicators.

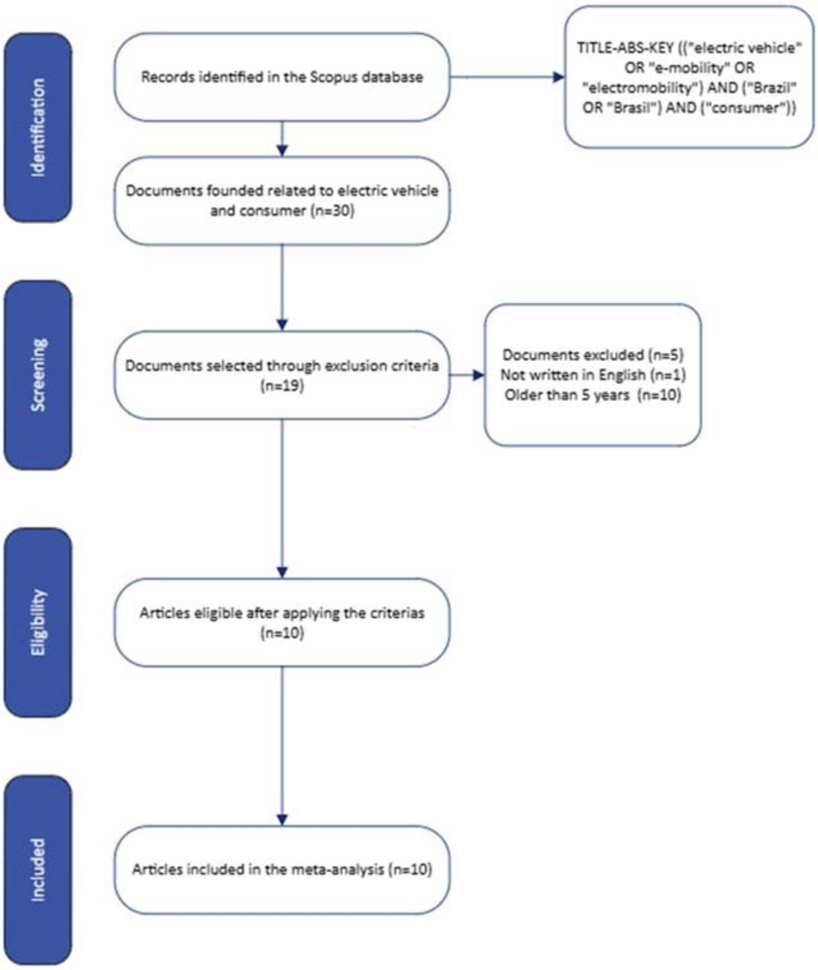

Fig. 1. PRISMA Methodology Flowchart.

2. Results and Discussion

This section presents an integrated analysis of the main findings derived from the two methodological approaches adopted in this study: a bibliometric mapping and a systematic literature review (PRISMA protocol). Together, these methods provide a comprehensive overview of scientific production on electric vehicle (EV) adoption in Brazil, highlighting research trends, knowledge gaps, and future directions.

The bibliometric analysis, based on 30 articles retrieved from Scopus prior to filtering, was conducted using VOSviewer software to visualize keyword co-occurrence and identify thematic clusters. In Figure 2, it is possible to observe the centrality of the term "Electric Vehicle" and its strong co-occurrence with keywords such as "technology", "cost", "policy", "infrastructure", and "environmental impacts"—revealing how the academic debate in Brazil is structured around macro-level issues related to energy transition and mobility.

To deepen the interpretation of the keyword network, five thematic clusters are examined below, offering a more granular perspective on how the literature articulates the main dimensions of the electromobility debate in Brazil.

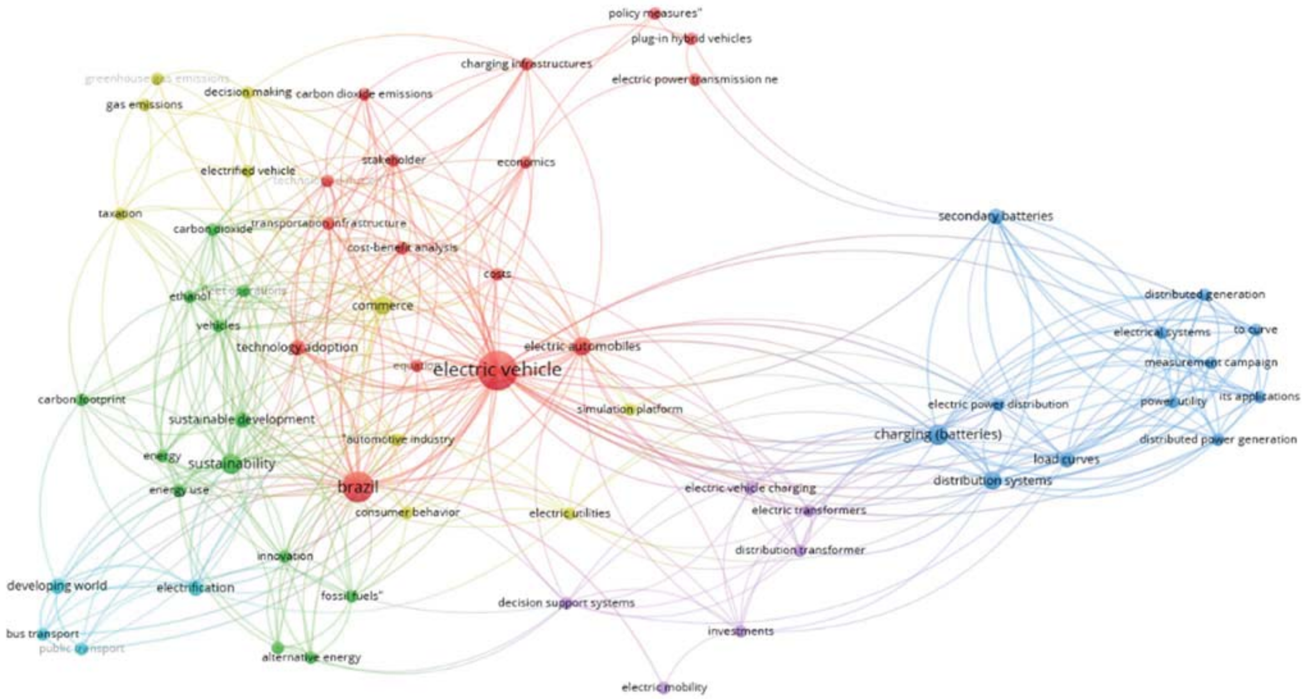

Fig. 1. Co-occurrence network of author keywords, clustered by thematic similarity.

2.1.1 Electric Vehicle

The term "Electric Vehicle" appears as the most prominent node in the red cluster, forming the conceptual core of the bibliometric network. It is strongly connected to terms like costs, technology adoption, policy, charging infrastructure, and CO_2 emissions. This dense interconnection suggests that the Brazilian academic community has centered the discussion on EVs around macro-structural dimensions of energy transition. Authors such as [8], [9], and

[14] emphasize the potential of EVs for reducing CO_2 emissions and promoting sustainable mobility, but also highlight the need for coordinated government actions, technological innovation, and public investment to overcome economic and infrastructural constraints.

2.1.2 Brazil

The keyword "Brazil" is part of the red cluster, close to technology adoption, cost, and policy, indicating that studies contextualize EV adoption within national-level institutional and infrastructural challenges. Authors such as [8], [9], [10], [11], and [17] point out structural limitations such as high acquisition costs, fragmented regulations, and insufficient public incentives. These associations reinforce that research in the Brazilian context is strongly concerned with how systemic barriers affect the implementation of electromobility strategies. The close link between "Brazil" and other policy-related terms highlights a research opportunity to develop localized frameworks and incentive mechanisms tailored to the country's economic and regulatory landscape.

2.1.3 Sustainability

The term "Sustainability" is situated in the green cluster, alongside terms like ethanol, innovation, emissions, and carbon footprint. This cluster represents a more ecological and long-term perspective in the literature, extending beyond vehicle use to broader lifecycle concerns. Studies such as [9] and [13] point to the environmental benefits of EVs, but also raise concerns about the sustainability of lithium-ion batteries, recycling policies, and the integration of renewable energy sources. The bibliometric map suggests an opportunity for further research into circular economy models, carbon market integration, and the social impacts of EV-related technologies in Brazil.

2.1.4 Charging Infrastructure

"Charging infrastructure" is also located in the red cluster, showing strong ties with cost, technology adoption, and policy. Its position as a secondary yet connected node suggests that, while it is not the core topic, it is frequently discussed as a crucial barrier. Authors such as [14], [15], and [16] highlight the unequal geographic distribution of charging stations—primarily in urban centers—and the absence of a unified national infrastructure strategy. The bibliometric visualization underscores the need for expanded studies on distributed energy systems (e.g., vehicle-to-grid—V2G), public-private partnerships, and regional disparities in EV accessibility, especially in underserved areas.

2.1.5 Consumer Behavior

Unlike the previous terms, "Consumer Behavior" is located in the yellow cluster, associated with nodes like commerce, market simulation, purchase intention, and acceptance. This cluster reveals a growing but less frequent focus in the literature on demand-side dynamics and user perception. Works such as [10], [12], and [13] explore how factors like trust in technology, environmental values, and perceived economic benefit influence the willingness to adopt EVs. The distance between this cluster and the red cluster (dominated by infrastructure and regulation themes) illustrates a disconnect in the field: while consumer perception is recognized as important, it is still underexplored relative to structural challenges. This gap signals an opportunity for future research to integrate behavioral models into national planning strategies.

To deepen the understanding of these gaps, a systematic literature review was conducted using the PRISMA protocol. From 30 initial articles, 10 were selected based on inclusion criteria (2020–2025, English, Brazil-focused) and full-text availability. These studies provided qualitative evidence on regulatory frameworks, market conditions, and behavioral factors, complementing the bibliometric findings with contextualized insights.

The selected works, detailed in Table 1, were analyzed using the EESG framework—Economic, Environmental, Social, and Governance—to synthesize the multidimensional nature of EV adoption. Economically, most articles highlight persistent cost barriers such as battery price, high taxation, and limited consumer credit, while also noting opportunities in energy efficiency and reduced operational costs [9], [11] and [16]. Environmental analyses confirm the relevance of Brazil's clean energy mix but also warn about battery waste and life cycle impacts [14] and [15].

Social aspects reveal gaps in public knowledge, cultural resistance, and the need for education and workforce training [10] and [12]. Meanwhile, governance issues—such as outdated regulations, lack of incentives, and fragmented responsibilities—remain major obstacles. Authors recommend integrated policies, partnerships, and better infrastructure planning to support the national transition to electromobility [8] and [17].

Reference	Countries	Economic	Environmental	Social	Governance
COSTA, Evaldo et al. (2021)	Portugal	High EV and battery costs require financial incentives; new business opportunities in battery/software sectors; gradual fleet integration enhances viability.	EVs help reduce emissions and promote climate goals; charging via renewables; tax exemptions support environmental benefits.	Affordability influences consumer preference; limited public information is a barrier; youth and eco-conscious individuals show higher acceptance; socio-demographic factors deserve attention.	Lack of clear regulations and coordinated policies; high taxation hampers progress; fiscal incentives and infrastructure support are needed; government should promote and regulate the market.
Oliveira, Marina Buranelli de et al. (2022)	Brazil	Tax incentives and lower operating costs are positives, but high purchase prices remain a key barrier; intent to buy depends on economic feasibility within a specific price range.	Positive perceptions of EVs stem from their environmental benefits; viewed as part of a modern, sustainable lifestyle.	Emotional appeal and personal attitudes drive adoption more than social norms; strong intent to buy even without prior experience.	Weak regulatory pressure; need for public strategies to support the EV market; findings could inform policy, industry, and marketing initiatives.
SCHVARTZ, Marceli Adriane et al. (2024)	Brazil	Cost-benefit analysis is crucial; financial incentives help overcome high upfront costs and limited infrastructure; positive link between economic factors and purchase decisions.	EVs are associated with emissions reduction, energy efficiency, and reuse; environmental values strengthen pro-sustainability behavior.	Psychological and cultural aspects shape adoption; innovation, modernity, and environmental awareness foster positive attitudes; regional factors influence perceptions.	Advocates for clear guidelines, public investments, and subsidies; calls for coordinated efforts between government and industry to expand infrastructure and market confidence.
VELHO, Sérgio Roberto Knorr et al. (2024)	Brazil	High initial EV and battery costs are barriers, but operational savings and fiscal incentives (e.g., MOVER, IPI Verde) support adoption.	Emission cuts and air quality improvements are expected, especially with Brazil's clean energy matrix and promotion of light/micromobility.	Cultural adaptation and workforce reskilling are needed; lack of collaboration (Triple Helix) hinders progress; behavioral studies are still limited.	Strong, coordinated public policies and programs (e.g., MOVER) are essential, but regulation and standardization remain insufficient.
FILHO, Flavio Garcia de Oliveira Soares et al. (2024)	Brazil	Perceived charging infrastructure value (PIT) and contextual influences (e.g., knowing EV users) affect purchase intent; readiness is a key factor.	Environmental concern relates to perceived green utility, but doesn't directly drive intention, revealing communication gaps.	Ease of use and subjective perceptions (e.g., autonomy, practicality) are crucial; peer influence also affects acceptance.	Recommends public policies to expand infrastructure and awareness; calls for standardization of charging points and institutional promotion.

Table 1. Main characteristics and key findings of the ten selected articles on electric vehicles in Brazil

Reference	Countries	Economic	Environmental	Social	Governance
YAMAMURA, Charles Lincoln Kenji et al. (2022)	Brazil	High purchase cost remains a challenge; local battery production is critical; $4.5–12B investment needed for charging infrastructure; scale requires design convergence.	85% renewable energy supports EV use; battery reuse/recycling and ethanol fuel cells are promising sustainable strategies.	Adoption depends on EV compatibility with routines; accessibility outside urban centers and recharge times are concerns; hybrids aid gradual transition.	Emphasizes regulatory clarity, technical standards, and infrastructure expansion; mentions PROCONVE and local bans as key actions.
RUOSO, Ana Cristina et al. (2022)	Brazil	High battery and tax costs; low profitability; suggests tax incentives, credit lines, leasing, and local production.	Zero emissions, renewable energy; concerns over battery disposal; circular economy proposed.	Benefits include better air and less noise; barriers are low awareness and cultural resistance.	Weak policies; calls for simplified taxes, PPPs, and stronger EV regulations.
ASSIS, Rodrigo Furlan de et al. (2023)	Brazil/Canada	High cost and taxes; advantages in maintenance and fuel; solutions include leasing, incentives, credit.	Zero emissions, renewable grid; challenges in disposal and fleet renewal; circular solutions suggested.	Gains in quality of life; barriers include low awareness and resistance; calls for campaigns and training.	Some progress in policy; gaps in coordination and planning; suggests frameworks, PPPs, and fleet policies.
CARVALHO, Enio Nascimento de et al. (2023)	Brazil	BEVs more efficient and cost-saving; hybrids also viable; fuel savings projected.	Low emissions; renewables up to 94% by 2050; EVs reduce fossil fuel reliance.	Quality of life benefits implied; tied to sustainability and efficiency.	Urges integration of energy and transport sectors; need for coordinated planning.
MORENO, Rodrigo et. (2020)	Chile, Brazil, UK	EVs and DG affect utility profits; proposes tariff reform and smart grids; warns of inefficient investments.	Smart grids and tariffs should support decarbonization and renewables.	Focus on energy access, reliability, and user roles in energy systems.	Regulatory reform needed; calls for adaptive, performance-based, inclusive policies.

Table 1 (continued)**.** Main characteristics and key findings of the ten selected articles on electric vehicles in Brazil

These PRISMA findings reinforce and expand the patterns observed in the bibliometric clusters. For instance, the economic and policy-driven barriers identified in the network align with the high frequency of discussions on cost and taxation in the reviewed studies. Likewise, the peripheral status of consumer behavior in the co-occurrence map is mirrored in the limited number of articles that address social acceptance in depth.

In summary, Brazilian EV research remains concentrated in structural and policy-related themes but is gradually incorporating environmental and behavioral dimensions. This convergence between quantitative and qualitative methods not only strengthens the robustness of the present study but also indicates promising directions for future interdisciplinary and inclusive research on sustainable mobility.

3. Conclusions

This study explored the scientific literature on the adoption of electric vehicles (EVs) in Brazil through an integrated bibliometric and systematic review, combining quantitative mapping with qualitative synthesis. The bibliometric analysis, conducted using VOSviewer, identified five central thematic clusters—electric vehicles, Brazil, sustainability, charging infrastructure, and consumer behavior—highlighting the complex and interdisciplinary nature of electromobility in the national context. The systematic review complemented these findings by reinforcing key barriers such as high acquisition costs, limited charging infrastructure, low public awareness, and fragmented institutional support, while also pointing to opportunities stemming from Brazil's clean electricity matrix and increasing societal interest in sustainable alternatives.

Despite certain methodological limitations, such as the use of a single database, the alignment between the bibliometric and systematic results strengthens the credibility of the conclusions.

Future research should focus on: (i) economic strategies to reduce upfront costs and enhance EV affordability, including local production and innovative financing mechanisms; (ii) the implementation of coordinated infrastructure policies that promote equitable access to charging stations; and (iii) stronger integration between public policies, industrial development, and consumer education. The insights presented here aim to support researchers, policymakers, and stakeholders in advancing a just and sustainable transition to electric mobility in Brazil.

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DISTRIBUTED ELECTRICAL VEHICLES STORAGE IN THE SPANISH ELECTRICITY MARKET: THE ROLE OF BALANCING SERVICES

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ABSTRACT
The accelerating adoption of Electric Vehicles across Europe, driven by the European Union's ambitious climate targets, is transforming both transportation and energy systems. Among the emerging solutions, Vehicle-to-Grid technologies offer promising avenues for enhancing grid flexibility and resilience.

This study investigates the economic viability of EVs functioning as a distributed energy storage network, capable of providing grid-balancing services through controlled charging and discharging. Using a genetic algorithm and 2024 electricity market data from Spain, the analysis models three scenarios: a stand-alone Battery Energy Storage System, EVs with controllable charging, and EVs with both charging and discharging capabilities. Two operational scopes are considered: exclusive participation in the day-ahead market, and combined participation in both the day-ahead and ancillary services markets.

The results highlight the potential of EV fleets to contribute to grid services while generating economic returns, particularly under the V2G model.

KEYWORDS
Electrical Vehicles, Vehicles to Grid, Economic Impact, Grid stability, Distributed Energy storage, Flexibility

INTRODUCTION
The rapid growth of Electric Vehicles (EVs) across Europe is reshaping the landscape of transportation and energy systems. Driven by the European Union's commitment to reduce greenhouse gas emissions from transport by 90% by 2050, the electrification of mobility has become a central pillar of the continent's climate strategy [1]. This transformation, however, brings with it significant challenges for the electricity grid, which must evolve to accommodate new patterns of demand, distributed energy resources, and the integration of millions of EVs.

The European Commission has identified the deployment of charging infrastructure and the development of smart grid capabilities as critical enablers of this transition. Without coordinated investment and planning, the increasing concentration of EV charging, particularly in urban areas and fleet depots, could strain local distribution networks and hinder the pace of electrification [2].

Leading consultancies echo these concerns. Some experts highlight the potential of vehicle-to-anything (V2X) technologies to support grid flexibility and resilience, especially when deployed at scale in fleet operations [3]. They also emphasize the need for integrated planning between mobility and energy sectors to ensure that infrastructure, regulation, and investment evolve in tandem [4].

In this context, intelligent energy systems, such as smart charging, distributed storage, and flexible grid management, emerge as key enablers for the smooth and sustainable integration of Electric Vehicles (EVs). While numerous studies have demonstrated the technical feasibility of EVs within the energy ecosystem, their economic viability remains less explored. Addressing this gap, the present study evaluates the economic impact of a simplified network of EVs operating as a distributed energy storage system connected to the grid.

The storage system analysed in this study is formed by aggregating EV chargers, enabling the provision of grid-balancing services through controlled charging and discharging processes. The main objective is to establish baseline profitability projections that offers preliminary insights into the economic viability of adopting the technology. These projections will later allow for the evaluation of the viability of distributed storage networks participating in the wholesale electricity market, based on specific criteria for each installation.

The study considers two operational scopes:

1. Exclusive participation in the day-ahead market
2. Participation in ancillary services (specifically tertiary regulation and replacement reserves), in combination with the day-ahead market.

A discontinuous operation scenario is analysed, where the battery energy storage system (BESS) can be charged or discharged at its rated power during any hour of the 24-hour period. This means that whenever the BESS is in charging or discharging mode, it operates at maximum power, but it does not necessarily reach full charge or complete depletion. This approach differs from continuous operation scenarios, where the BESS charges or discharges at rated power until reaching its energy limits. The distributed storage network (EV fleet) is evaluated under the following scenarios, each analysed under both operational scopes:

- Stand-alone BESS (Battery Energy Storage System), used as a reference case.
- Electric vehicles with controllable charging (V1G model).
- Electric vehicles with controllable charging and discharging (V2G model).

This document is structured into several sections. First, a review of the state of the art is presented, followed by an overview of the electricity markets in Spain. Next, the methodology is described, the results are presented, and finally, the conclusions are discussed.

BACKGROUND

There is a vast body of literature focused on Electric Vehicles (EVs) [5], tracing back to the early 1800s when Robert Anderson designed the first electric carriage in Scotland in 1832. While interest in EVs has persisted over the centuries, the true turning point for transport decarbonization began in the last decade. This new era was marked by the rise of private companies, policies and legislation, which have driven the widespread adoption of electrified transport [4], [6].[7].

Moreover, electric vehicles (EVs) can interact with the power grid through a Vehicle-to-Grid (V2G) model, where the charging system is bidirectional. In this setup, EVs can not only draw energy from the grid but also supply energy back to it [6], [8] , [9]. This operational model generally benefits the electrical system by supporting renewable energy integration, improving energy efficiency, enhancing power factor, enabling energy savings, and facilitating load management through controlled demand distribution [8].

A key aspect of EV integration is the optimal coordination between Renewable Energy Storage Systems (RESS) and green energy sources to support transport electrification [10]. To ensure effective RESS operation, it is crucial to consider system sizing, which helps minimize energy losses and maintain voltage stability. Several studies have analysed the technical feasibility of this integration by modelling it as an optimization problem, such as in the IEEE 69-bus system [11], [12].

Another significant advantage of EVs is their potential to alleviate transmission line congestion. Research has demonstrated that EVs can contribute to mitigating congestion within the European grid framework, even providing quantifiable demand redispatch values for conventional power sources [13].

However, large-scale EV deployment can also have negative impacts on the power system. Studies indicate that a massive influx of EVs into the grid may lead to adverse effects, including frequent fluctuations in power supply and demand, as well as oscillatory patterns and consumption variation [9]. Additionally, issues such as harmonic distortion, caused by the nonlinear characteristics and converters of EV chargers; overcurrents due to load variations, and voltage fluctuations related to charging rates and integration levels have been observed. [8]

These impacts can be mitigated through appropriate system design, which includes careful consideration of EV fleet size, charger location, and the implementation of effective control strategies, as described in several studies [9].

From a technical perspective, transport electrification is feasible and even advantageous. It offers environmental benefits, supports renewable energy integration, and provides ancillary services to the grid. However, none of the aforementioned studies have thoroughly addressed the economic viability of this technology. There is a notable lack of research analysing sustainable business models for EV integration.

Some studies that consider the economic aspects of electric vehicles (EVs) focus solely on the cost savings compared to internal combustion engine vehicles, particularly in terms of fuel consumption. These studies typically assume that EVs only participate in unidirectional charging (V1G), without accounting for the potential benefits of bidirectional charging and grid services (V2G) [4].

EVs can provide additional value by supporting the electrical grid during periods when they are not in use for transportation. A study discusses the benefits of grid integration from the perspective of various stakeholders in the electricity market. It highlights that generation companies can increase their profits through improved demand control and energy price management. System operators benefit from reduced losses, peak shaving, peak shifting, and increased power transfer capabilities. EV aggregators can enhance their revenues both from utilities and end users, while users themselves benefit from cost minimization [14].However, this study does not provide any quantitative figures or estimates of the potential economic gains.

Another study explores dynamic optimization by modelling price fluctuations to determine the financial return of V2G participation. Based on a real-world V2G case, it estimates a profit of approximately 2€/EV·year [15]. Nevertheless, this analysis does not consider all possible market mechanisms, such as Automatic Frequency Restoration Reserve (aFRR), Manual Frequency Restoration Reserve (mFRR), or Replacement Reserve (RR). These segments of the electricity market could play a decisive role in decision-making processes.

Therefore, the objective of this study is to analyse the economic viability of a distributed battery system composed of electric vehicles (EVs), considering participation in the day-ahead market, Manual Frequency Restoration Reserve (mFRR), and Replacement Reserve (RR). The characteristics of these markets are described in the following section

MARKECT DESCRIPTION

Day-Ahead Market: This is the main wholesale electricity market in terms of both energy volume and economic value. Generators and consumers submit bids for each hour of the following day. A centralized European matching process is carried out using the Euphemia algorithm. The market operates under a marginal pricing system and is held once per day.

Automatic Frequency Restoration Reserve (aFRR): This service acts automatically to maintain system frequency (50 Hz) and balance generation and demand in real time. It is activated within seconds and can be sustained for several minutes. Due to the rapid response required, it is not suitable for storage systems based on electric vehicles.

Manual Frequency Restoration Reserve (mFRR): This reserve is manually activated to restore the capacity of the secondary regulation. It has an activation time of up to 12.5 minutes, is organized into 96 periods of 15 minutes each, and can be sustained for up to 29 minutes. It is divided into upward and downward markets and is also settled using a marginal pricing system.

Replacement Reserve (RR): This reserve is activated after the tertiary reserve to replenish reserves and address large imbalances. It is managed through the European TERRE platform. The duration ranges from 15 to 60 minutes, with activation occurring 30 minutes in advance. Like mFRR, it is settled separately for upward and downward regulation under a marginal pricing system.

Additionally, there are intraday markets that allow for the correction of deviations between forecasted and actual generation or demand. However, these are not considered in this study, as electric vehicle systems are not expected to participate in them.

METHODOLOGY

To assess the economic impact of different electricity markets on a distributed storage system composed of electric vehicle (EV) batteries available for grid services, and to analyse its economic viability, it is necessary to determine the charging and discharging profiles for each of the scenarios considered: Stand-Alone (as a reference), V1G, and V2G.

These profiles are defined using a genetic algorithm based on electricity market prices from a reference year, assuming that the price for selling and buying energy is the same. For this analysis, publicly available energy sale prices from the year 2024 have been used, without considering any additional costs associated with energy purchases. The year 2024 is considered representative of upcoming years due to the existing renewable energy mix, which contributes to the characteristic "duck curve," and because the influence of the war in Ukraine has significantly diminished.

The objective of the algorithm is to maximize the economic benefit derived from storage management, while complying with the established operational constraints:

- Net daily energy balance: Zero net energy exchange over the day.
- Power capacity: Equal to the total contracted access power.
- Single-node modelling: A reference battery of 1 MW/3 MWh is used.
- Battery characteristics: Internal losses, degradation, and specific material properties are not considered.
- Price profiles: Based on electricity market prices from the year 2024. Assuming that the price for selling and buying energy is the same
- Availability: The asset is assumed to be available for operation 24 hours a day.
- Number of cycles: At least one full charge-discharge cycle per day.
- Discharge condition: Discharging is only allowed if there is stored energy available.
- End-of-day condition: If energy remains stored at the end of the day, the algorithm forces a discharge to bring the state of charge to zero during the final hours.
- Energy balance constraint (only VxG): Vehicles are required to charge 3 MWh more than they discharge each day. This is meant to represent the consumption of energy due to the normal use of the EV.

The algorithm is executed iteratively, as illustrated in the flow-chart diagram in Fig. 1. The process begins with an initial population generated randomly. Each generation undergoes a fitness evaluation, followed by selection, crossover, and mutation operations, until convergence is achieved toward the most economically optimal strategy. Monthly simulations are performed, with each day modelled independently to enhance the accuracy of the results.

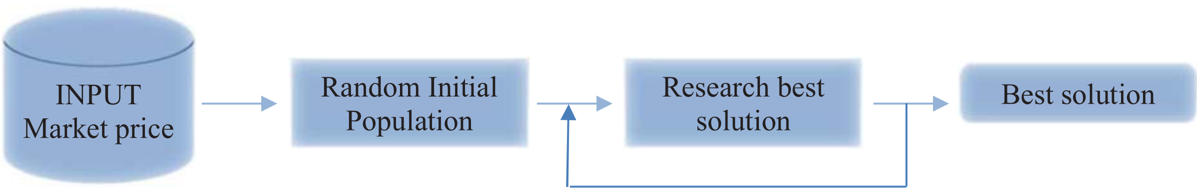


Fig. 1. Flow-chart diagram. Genetic algorithm

After determining the operating profile of the storage system, the hourly energy cost and revenue is calculated as the product of the energy exchanged during each hour and the corresponding market price, depending on the electricity market in which the system operates.

The economic benefit is then calculated as the difference between the revenue generated from selling energy during battery discharge and the cost of purchasing energy for charging.

RESULTS

The results of the three scenarios analysed are presented below, each detailed in a separate subsection.

Stand-alone BASE case

The first result corresponds to the operating profile generated by the optimization algorithm operating in the day-ahead market. As an example, Fig. 2 presents a sample of 264 hour . In this figure, the market price is shown as a continuous blue line, while the charging and discharging periods are represented by bars—green for discharging (positive values) and red for charging (negative values). The horizontal axis represents time hourly.

The graph demonstrates that charging occurs during periods of lower market prices, while discharging is concentrated during hours with higher prices.

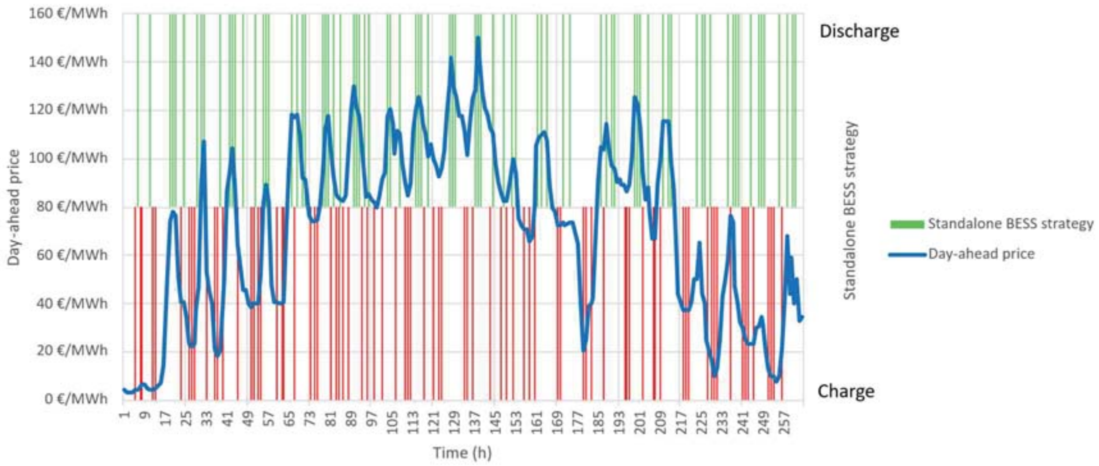


Fig. 2. BESS Operation example (Vertical grey lines indicate day boundaries).

The charging and discharging operational strategy dealing solely in the day-ahead market yields an annual profit of 40 €/MW. Total revenues amount to 178 €/MW, while energy costs reach 138 €/MW. The battery operates for a total of 5,292 hours per year. This value is aligned with the standard market considering the constrains described in the methodology [16]. This way of operation is considered as reference.

When participating in balancing markets, the operational strategy and resulting profit are recalculated. In this case, the price does not correspond solely to the day-ahead market but rather reflects a combination of prices from the different markets. The effectiveness of the optimized profile in capturing price opportunities can be observed in Fig. 5.

To better understand the asset's behaviour under this operational strategy, the distribution of energy, associated costs and revenues, and operating time across each market are presented. It is important to highlight that when energy is purchased, transactions in the mFRR and RR markets always occur in the downward direction. Conversely, when energy is sold, participation in the mFRR and RR markets is always in the upward direction. The results have been normalized to the reference, the BESS Stand-alone operating in Day-ahead market.

Table. 1. Results Stand-alone operating in Day-ahead, mFRR and RR market

	Day-ahead	mFRR	RR	TOTAL
Energy purchase [a.u.]	0.6 38.3%	0.5 32.1%	0.4 29.6%	1.5
Energy sale [a.u.]	0.8 51.5%	0.4 26.0%	0.3 22.4%	1.5
Cost of energy purchase [a.u.]	0.5 74.1%	0.1 8.5%	0.1 17.4%	0.7
Revenue from energy sale [a.u.]	0.9 50.3%	0.5 25.7%	0.5 24.1%	1.9
Profit [a.u.]	2.4 40.7%	1.9 32.6%	1.6 26.8%	5.9
Time spent purchasing Energy [a.u.]	0.6 39.3%	0.5 31.7%	0.5 29.0%	1.6
Time spent selling Energy [a.u.]	0.8 52.1%	0.4 25.7%	0.4 22.1%	1.6

Since the values, in the Table 1, are referenced to a baseline, those greater than zero indicate an increase, while those below zero reflect a decrease. In the case of the BESS, participating in all three electricity markets significantly boosts the energy throughput, operating hours, revenues, and profits (5.9 a.u.), which reach almost six times higher. Additionally, energy purchase costs are reduced (0.7 a.u.), despite a higher volume of energy being acquired. As conclusion, the additional profit derived from participating in balancing markets is notably substantial when compared to operating exclusively within the Day-ahead market.

Unidirectional charging case (V1G)
In this case study, the storage system consists of electric vehicle (EV) batteries, which are only capable of charging and do not have the capacity to sell energy back to the grid. As a result, there is no revenue generated, only energy purchase costs. The objective of this scenario is therefore to minimize energy expenditure. This case study is specifically relevant to profitability projections because it faces a much lower barrier to entry than its V2G counterpart. Likewise, a V1G operating system can spearhead further development in the provision of flexibility.

Fig. 3 presents a sample period (264 hour), where the algorithm identifies the lowest-priced hours for charging the battery. As in the previous case study, the market price is shown as a continuous blue line, while charging periods are represented by red bars (negative values). The horizontal axis indicates the time hourly.

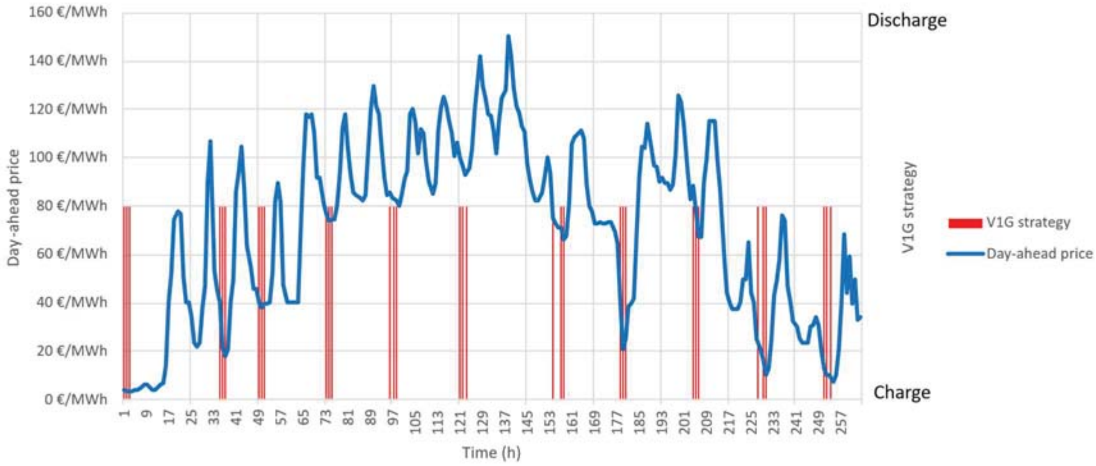


Fig. 3. V1G Operation example (Vertical grey lines indicate day boundaries).

When operating exclusively within the Day-ahead market, the system incurs an annual energy cost of 0.4 a.u., with the battery functioning for 0.4 a.u. hours over the year. This results in a net benefit of -1.4 a.u. relative to the reference value, indicating a loss when compared to alternative strategies.

When participating in balancing markets, the demand-side operating strategy is recalculated to account for all available market options. The effectiveness of the optimized profile in capturing price opportunities is presented in Fig. 5.

The distribution of energy associated costs and revenues, and operating time across each market is summarized in Table. 2.

Table. 2. Results V1G operating in Day-ahead, mFRR and RR market

	Day-ahead	mFRR	RR	TOTAL
Energy purchase [a.u.]	0. 2 20.1%	0.4 42.8%	0.34 37.0%	0.9
Energy sale [a.u.]	-	-	-	-
Cost of energy purchase [a.u.]	0. 1 34.2%	0.1 47.3%	0.0 18.6%	0.1
Revenue from energy sale [a.u.]	-	-	-	-
Profit [a.u.]	-0.2 34.2%	-0.2 47.3%	-0.1 18.6%	-0.5
Time spent purchasing Energy [a.u.]	0.1 24.5%	0.2 42.4%	0.1 33.1%	0.4
Time spent selling Energy [a.u.]	-	-	-	-

When the system operates across all three electricity markets, it achieves a lower annual energy cost compared to the baseline, due to reduced energy purchases and shorter operating time. However, the net benefit remains negative, as no actual revenue is generated. Still, this strategy performs better than operating exclusively in the Day-ahead market, as it reduces energy costs while increasing operating time, resulting in a less negative overall outcome. Notice that in this case is no the Day-ahead market the more significant.

Bi-directional charging case (V2G)
In this case study, the chargers allow for bidirectional energy flow, meaning that the EV batteries can both charge from the grid and discharge energy back to it, thereby providing grid services. As a result, the EV-based storage system behaves similarly to a stand-alone system, generating revenue from energy sales and incurring costs from energy purchases. As previously mentioned, this scenario assumes that the amount of energy charged must exceed the discharged energy by 3 MWh per day, to account for the energy consumption of the vehicles for transportation purposes.

Fig. 4 shows how the genetic algorithm, operating in the day-ahead market, successfully identifies the most favourable moments for both charging and discharging based on market prices. In the graph (sample of 264 hour), the market price is shown as a continuous blue line, while charging periods are represented by red bars (negative values). The vertical axis indicates the time of day.

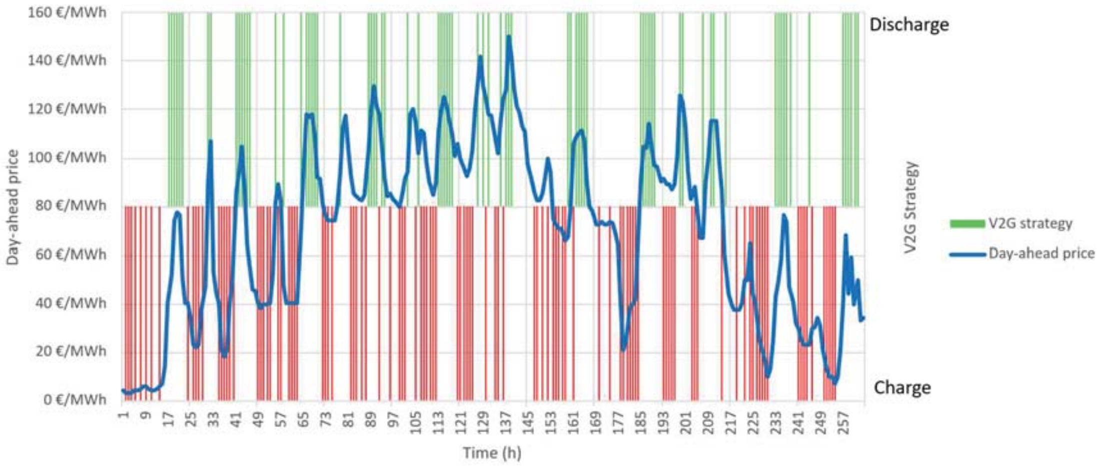


Fig. 4. V2G Operation example (Vertical grey lines indicate day boundaries).

In this scenario, where the system operates exclusively in the Day-ahead market, total annual revenue decreases to 0.9 a.u., while energy costs increase to 1.3 a.u., both relative to the reference. This leads to a negative profit of -0.2 a.u., indicating that the strategy is not economically viable on its own.

In this study case when participating in balancing markets, both the demand and generation-side operating profiles are recalculated to account for all available market options. The effectiveness of the optimized profile in capturing price opportunities is presented in Fig. 5.

The distribution of energy associated costs and revenues, and operating time across each market is summarized in Table. 3. When energy is purchased, in the mFRR and RR markets always occur in the downward direction, and when energy is sold, participation in the mFRR and RR markets is always in the upward direction

Table. 3. Results V2G operating in Day-ahead, mFRR and RR market

	Day-ahead	mFRR	RR	TOTAL
Energy purchase [a.u.]	1.0 32.6%	1.1 33.1%	1.1 34.3%	3.2
Energy sale [a.u.]	0.7 30.9%	0.9 35.8%	0.8 33.4%	2.4
Cost of energy purchase [a.u.]	0.6 68.1%	0.1 11.9%	0.2 20.0%	0.8
Revenue from energy sale [a.u.]	0.7 46.7%	0.4 28.4%	0.4 24.8%	1.5
Profit [a.u.]	1.2 30.5%	1.5 40.9%	1.1 28.5%	3.8
Time spent purchasing Energy [a.u.]	0.7 38.3%	0.6 31.8%	0.5 29.8%	1.8
Time spent selling Energy [a.u.]	0.6 49.6%	0.4 28.0%	0.3 22.4%	1.3

In the case of V2G, comparing the two market strategies, operating solely in the Day-ahead market versus including Ancillary Services; the system shifts from generating losses to achieving profits (3.8 a. u.), reaching up to four times the reference value of the study. When comparing the results to the baseline, there is a higher energy throughput, longer operating hours, increased revenue from energy sales (2.4 a. u.), and lower energy purchase costs (0. 8 a. u.), all of which contribute to the significant improvement in profitability. The main market in this operation mode is the Day-ahead market.

Comparison results

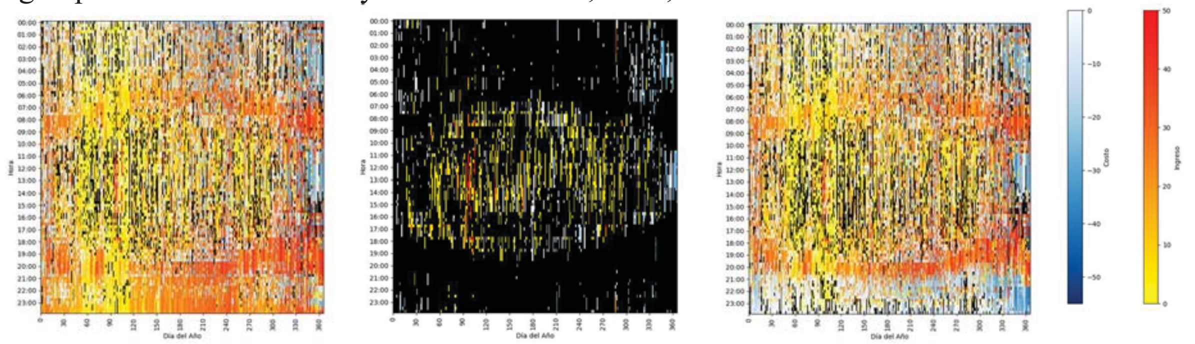
Allowing for energy discharge provides a substantial advantage compared to a charging-only operation model. However, the comparison between a stand-alone battery system and a distributed storage system based on electric vehicles will always be less favourable for the latter. This is because distributed storage systems serve purposes beyond market participation: the transportation of people and goods.

Table. 4. Summary Results

	Time spent purchasing energy [h]	Time spent selling energy [h]	Cost of energy purchase [€/MWy]	Revenue from energy sale [€/MWy]	Profit [€/MWy]
Stand-alone (Day-ahead)	1	1	1	1	1
V1G (Day-ahead)	0.4	-	0.4	-	-1.4
V2G (Day-ahead)	1.4	1.0	1.3	1.0	-0.2
Stand-alone (Day-ahead, mFRR & RR)	1.6	1.6	0.7	1.9	5.9
V1G (Day-ahead, mFRR & RR)	0.4	-	0.1	-	-0.5
V2G (Day-ahead, mFRR & RR)	1.8	1.3	0.8	1.5	3.8

Participation in markets beyond the day-ahead market proves to be more beneficial in all the cases analysed. Furthermore, the V2G model offers greater advantages compared to V1G technology, due to the possibility of selling energy back to the grid. On the other hand, conventional stand-alone storage systems show higher benefits, as the distributed system based on EV batteries must serve both transportation needs and the electrical grid.

Fig. 5 presents the three analysed cases: BESS, V1G, and V2G.



Stand-alone V1G V2G

Fig. 5. Headmaps market operation (Day-ahead, mFRR & RR)

Fig. 5 heatmaps show how the different storage systems operate in their respective markets to maximize profits working with the three markets prices. The heatmaps display the revenues and costs of each strategy, using a white-to-blue scale for costs, a yellow-to-red scale for revenues, and black to indicate periods when the battery is inactive.

As shown in the graphs, periods with high prices display columns with strong blue-red contrast, since these high prices result in both high purchase costs and high sales revenues. In contrast, periods with lower prices are characterized by white and yellow columns.

Another trend in revenues is the appearance of horizontal bands that separate during the central months and converge at the beginning and end of the year. This pattern reflects the interaction between two factors: demand peaks and solar generation. Solar generation is highest during the central months and around midday, which leads to lower revenues and makes it a better time to purchase energy.

The discharge limitations in the V2G scenario reduce the total duration of participation periods, as each charge limits the capacity for future discharges. This results in V1G scenario heatmaps appearing much darker than those of scenarios that allow discharge, such as BESS and V2G.

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CONCLUSIONS

A study has been conducted on the operation of electric vehicle (EV) batteries, understood as a distributed energy storage system, and their potential participation in grid services available to market participants. Current regulations limit the development of such projects by requiring a minimum capacity of 1 MW per participation in the mFRR and RR services.

The behaviour of a controllable EV fleet in the wholesale electricity market has been analyzed under two operational modes: as consumers only (V1G) and as both consumers and generators (V2G). These scenarios were compared against a benchmark case of a 3-hour stand-alone battery energy storage system (BESS).

The main conclusions of the study are as follows:

Distributed storage systems offer advantages in terms of flexibility and cost, although they require a sufficiently large fleet—exceeding one megawatt—to comply with regulatory requirements.

Effective participation in balancing services is a key factor in improving the expected profitability of EV operation in the wholesale electricity market.

In all scenarios, profitability improved when participating in all available markets. It is therefore concluded that proper integration into ancillary service markets significantly enhances the profitability of an asset, within the assumptions defined in this study.

V1G technologies offer an immediate both to distributed storage owners and grid operators, providing an incumbent flexibility providing asset whilst garnering significant expenditure savings.

Further research is required to obtain down-to-earth projections that may be used to evaluate a particular deployment of these strategies. These may include relevant factors for profitability such as network rates and tolls in energy purchasing price, battery degradation or uncertainty in ancillary service market availability.

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HEAT PIPE SOLAR COLLECTOR WITH GRAPHENE OXIDE NANOFLUID: THERMAL PERFORMANCE STUDY

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ABSTRACT

The growth of global energy consumption and the commitments to reduce emissions highlight the urgent need for renewable technologies. Among these, solar thermal systems stand out as a promising alternative to increase energy efficiency and mitigate environmental impacts [1]. Evacuated tube solar collectors assisted by heat pipes exhibit higher efficiency and the ability to operate at elevated temperatures when compared to conventional systems [2]. At the same time, the use of nanofluids has shown great potential to enhance heat transfer, presenting thermal properties superior to those of their base fluids [3]. This study aimed to experimentally evaluate the thermal performance of an evacuated tube solar collector assisted by heat pipes operating with graphene oxide nanofluid. The system was installed at a 25° inclination (corresponding to the latitude of Ponta Grossa, Paraná, Brazil) and tested under real meteorological conditions. Thermal efficiency was determined based on the First Law of Thermodynamics. The results indicated efficiency values of 80.7% on a cloudy day and 88.0% on a sunny day, significantly surpassing the average efficiency of conventional solar collectors, typically around 30% [4]. These findings demonstrate the potential of the proposed system for water heating applications, both in residential and industrial settings. In conclusion, the integration of graphene oxide nanofluids into evacuated tube solar collectors assisted by heat pipes represents a viable and sustainable solution, capable of contributing to energy efficiency while reducing environmental impacts [5].

KEYWORDS
Solar Thermal Energy, Heat Pipe, Graphene Oxide Nanofluid.

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DOES ELECTRIC VEHICLES AS PART OF THE CITY FLEET DECREASE AIR POLLUTANTS? CASE STUDY IN A BRAZILIAN CITY

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ABSTRACT

The use of fossil fuels in the automotive sector is still significant, and the incomplete combustion of these fuels produces carbon monoxide (CO) that, when inhaled, can form carboxyhemoglobin, reducing the transport of oxygen to the cells. Several studies indicate an association between exposure to CO, even at low concentrations, and mortality from cardiovascular diseases. In this sense, the growing adoption of electric vehicles can be seen as an alternative to reduce pollutant emissions and, consequently, improve air quality and public health. Therefore, the present study aimed to simulate CO dispersion in a scenario where the current fleet of diesel-powered buses in a medium-sized city (approximately 450,000 inhabitants) was replaced by electric buses. The city of Ponta Grossa, in the state of Paraná, Brazil, was considered as a case study. The simulations were carried out using computational fluid dynamics (CFD) with ANSYS/FluentTM 19.1 software. Ponta Grossa is the ninth most populous city in southern Brazil and, a two square blocks were considered in the simulation, near a shopping center, a bus terminal and an Environmental Complex, with intense circulation of people and vehicles. The vehicular fleet in the studied region was counted during peak hours (between 12–1 p.m. and 6–7 p.m.) on weekdays, totaling an hourly average of 64 trucks, 532 motorcycles, 4,000 cars, and 308 buses. The CO concentration in the current scenario (diesel-powered buses) was 14.4 ppm, above the national air quality of 9 ppm), thus falling into the “attention” air quality index. Conversely, when replacing the bus fleet with electric vehicles, there was a reduction of 1.2 ppm (8.3%). The results highlight the importance of encouraging the use of electric vehicles. As future work, it would be relevant to simulate the replacement of cars powered by fossil fuels/biofuels with electric vehicles, since they are the largest share of the urban fleet.

KEYWORDS:
Electric Buses, Computational Fluid Dynamics, Carbon Monoxide.

BEHAVIOR OF PEARLITIC STEELS AGAINST HYDROGEN EMBRITTLEMENT: PERSPECTIVES FOR TRANSPORT AND STORAGE IN LOW-CARBON HYDROGEN SYSTEMS

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ABSTRACT

The advancement of clean energy technologies, especially low-carbon hydrogen systems, requires materials with high mechanical strength and reliability when exposed to hydrogen. In this study, the behavior of pearlitic steels subjected to hydrogen embrittlement was evaluated by combining microstructural and mechanical characterizations with electrochemical charging tests in NaCl solution. The results showed a significant reduction in ductility and tensile strength after hydrogen charging. This behavior was associated with the high density of ferrite/cementite interfaces and the presence of fragmented cementite, which act as preferential hydrogen trapping sites, promoting crack nucleation and propagation through mechanisms such as Hydrogen Enhanced Localized Plasticity (HELP). These findings highlight the high susceptibility of pearlitic steels, even when presenting good initial strength, to severe degradation in hydrogen-containing environments. Thus, the importance of investigating and improving conventional materials to enable their use in hydrogen transport and storage is emphasized, considering the challenges related to safety, the costs of adapting existing infrastructures, and long-term reliability. By establishing the relationship between microstructure and susceptibility to embrittlement, this work contributes to material selection strategies that ensure the safe and efficient implementation of sustainable energy systems based on low-carbon hydrogen.

KEYWORDS

Pearlitic steel; low carbon; embrittlement.

INTRODUCTION

Since the last century, fossil fuels have consolidated as the main source of energy in several strategic sectors of society and the economy, being widely employed in industry, transportation, and power generation. However, their use is directly associated with high carbon dioxide (CO_2) emissions, which intensify the greenhouse effect, accelerate the degradation of natural resources, and contribute to global warming [1].

In light of this issue, in recent decades, different nations and international organizations have intensified efforts in the search for sustainable alternatives, promoting emission reduction programs and energy transition strategies. In this context, low-carbon hydrogen emerges as a promising alternative, standing out due to its high energy density per unit mass, abundance in nature, and the absence—or significant reduction—of CO_2 emissions during its use, when compared to conventional sources [2,3].

Despite its socio-environmental advantages, the large-scale adoption of hydrogen still faces several challenges. Among them are the high production costs, the need to establish a sustainable consumer network, and, above all, the difficulties related to its transport and storage, particularly when carried through pipelines or stored in steel tanks [4].

One of the main obstacles is hydrogen embrittlement (HE), a phenomenon in which atomic hydrogen diffuses into the metallic material, interacts with its crystalline structure, and promotes significant changes in mechanical properties, such as the reduction of ductility and the induction of premature failures. This effect directly compromises the reliability and safety of steels employed in critical applications, making it especially relevant in the context of long-term hydrogen transport and storage [4,5].

Susceptibility to embrittlement depends strongly on the steel microstructure and the operating conditions. In this regard, pearlitic steels represent a strategic subject of study, as they combine mechanical strength, ductility, and economic viability. Widely used in railway tracks, high-strength wires, and flexible pipeline components, these steels also stand out as potential candidates for applications involving low-carbon hydrogen. Nevertheless, their performance against HE still requires detailed investigation, especially considering the requirements of pressure, safety, and durability imposed by pipelines and other transport systems [6].

Furthermore, although the use of existing natural gas networks for hydrogen transport is an economically attractive alternative, this practice demands robust investments in infrastructure adaptations, due to additional risks of corrosion, embrittlement, and the higher energy required for gas compression [7].

In this scenario, the present research aims to investigate the behavior of a pearlitic steel under hydrogen embrittlement, with emphasis on the influence of its microstructure on mechanical strength and susceptibility to the phenomenon. From this study, it is intended to understand to what extent such materials may be compromised by the presence of hydrogen and to assess their potential for application in transport and storage systems. Thus, this work seeks to contribute to the selection of suitable alloys and to the safe and efficient development of sustainable energy infrastructures, in alignment with global decarbonization efforts.

MATERIALS AND METHODS

The material used in this study consisted of samples of a pearlitic steel originally shaped as a railway rail, which was sectioned into specimens with dimensions suitable for each test. The chemical composition, determined by optical emission spectroscopy, was as follows in mass percent: Fe–0.75C, 0.82Mn, 0.34Cr, 0.22Si, 0.10P, 0.01Mo, and traces of Ni.

Initially, the material’s as-received condition was evaluated, i.e., without the application of additional thermal or mechanical treatments. These samples were referred to throughout the study as W.T. (without treatment). The main objective was to analyze the behavior of a material already widely used in critical applications when subjected to hydrogen loading conditions.

For microstructural characterization, the samples were mounted in bakelite, ground with water sandpapers ranging from 120 to 600 grit, and polished with diamond pastes of 6, 3, and 1 μm. Microstructures were revealed using a 4% Picral solution for optical microscopy analyses and a 2% Nital solution for scanning electron microscopy (SEM).

Optical observations were conducted using a Leica DMI 3000M microscope, at magnifications of 200× and 500×, while higher-resolution analyses were performed on FEI® Quanta 450 and FEI® Quanta 650 equipment, at magnifications of 8,000× and 10,000×, allowing the evaluation of the pearlite interlamellar spacing. The obtained micrographs were subsequently processed and analyzed using Fiji ImageJ® software, enabling quantitative characterization of the microstructures formed under each condition.

Considering that pearlitic steels are widely used as tensile reinforcement in risers and that hydrogen transport through pipelines may occur under similar conditions, hydrogen charging was carried out through electrochemical tests.

For this purpose, a 3.5% NaCl solution was used, representing a corrosive medium analogous to that found in oil pipelines, gas pipelines, and offshore structures intended for low-carbon hydrogen. The electrochemical tests included open-circuit potential (OCP) measurements, with a stabilization time of 3600 seconds (1 hour), and potentiodynamic polarization, conducted between 0 and –2 V relative to the OCP at a scan rate of 1 mV/s.

The samples, previously cold-mounted, ground between 220 and 600 grit, cleaned with alcohol, and dried, were used as the working electrode. The reference electrode was Ag/AgCl/KCl (sat.) and the counter electrode was platinum. At the end of the tests, the polarization curves were normalized with respect to the exposed area and used for result analysis.

Hydrogen charging was performed in the same electrochemical cell used for cathodic polarization tests, replacing the working electrode with the tensile specimens. These specimens were machined according to ASTM E8 specifications, with dimensions shown in Fig. 1, and were prepared individually for each microstructure studied.

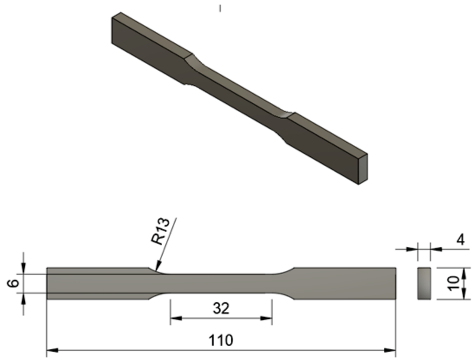

Fig. 1. Schematic drawing of the machined tensile specimen.

The hydrogenation process was conducted using the chronoamperometry technique, with exposure periods of 3 hours at room temperature, and all tests were performed in triplicate to ensure reproducibility. During these tests, the cathodic potential previously determined through polarization tests was applied.

The specimens, properly machined and thermally treated for each microstructure, underwent mechanical grinding over the entire gauge length using water sandpapers ranging from 220 to 600 grit. Subsequently, the samples were cleaned with 70% ethyl alcohol and dried with an electric dryer to remove surface roughness, imperfections, and residual impurities from the machining process. Afterwards, the ends of the specimens were coated with insulating materials to minimize hydrogen absorption on surfaces outside the region of interest. For this coating, a first layer of Kapton tape was applied, followed by a second layer of Teflon tape. After this preparation step, the dimensions of the regions of the specimens to be exposed to hydrogen charging were defined.

Finally, uniaxial tensile tests were carried out on an EMIC DL-10000 universal testing machine at room temperature, following ASTM A370 and ABNT NBR ISO 6892 standards, with a testing speed of 5 mm/min. From these tests, the stress–strain curves were obtained, as well as the mechanical parameters: yield strength (YS), ultimate tensile strength (UTS), fracture stress (FS), and percent elongation (El.).

RESULTS AND DISCUSSION

The samples were characterized by optical microscopy (OM) and scanning electron microscopy (SEM) to highlight the microstructural differences resulting from the applied thermal treatments. The optical microscopy analysis, shown in Fig. 2a (etched with 4% Picral), reveals the material's microstructure in the as-received condition. The presence of deformed grains is observed, a typical feature resulting from the mechanical manufacturing processes.

The microstructural distinction becomes even more evident in the images obtained by SEM. Fig. 2b, which shows the as-received condition at higher magnification, confirms the presence of a lamellar structure with a more uniform orientation and reduced interlamellar spacing. This microstructural configuration is consistent with the slight increase in hardness measured for this condition, which was 31 HRC.

Additionally, the presence of cementite particles, of a brittle nature, is identified within the microstructure. Their origin is likely associated with previous thermal treatments undergone by the material during its manufacturing stages, such as welding processes.

a- b-

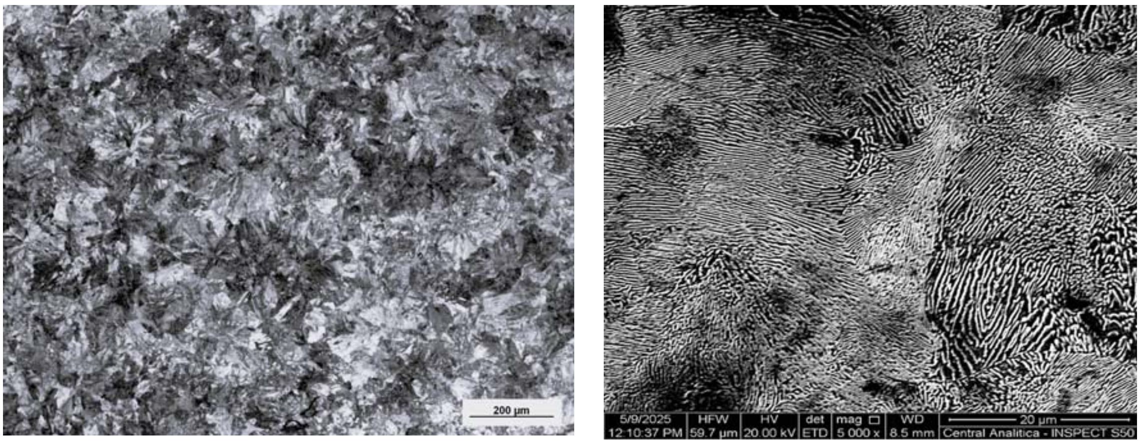

Fig. 2.a Optical micrograph (4% Picral). Fig. 2b Scanning Electron Micrograph (SEM) (2% Nital).

The results of the open-circuit potential (OCP) tests in a 3.5% NaCl solution are presented in Fig. 3. It can be observed that both samples reached potential stabilization over 3600 seconds, showing only minor fluctuations during the initial stage of the test. The as-received (CR) condition exhibited an average potential value of –0.521 V.

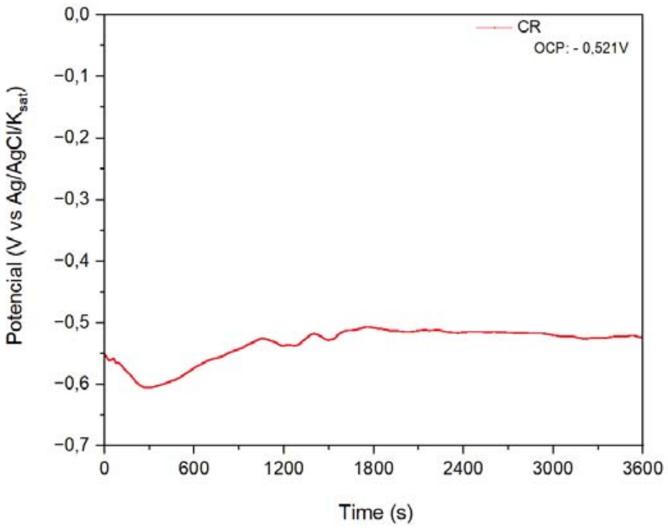

Fig. 3. Open-Circuit Potential (OCP) in 3.5% NaCl solution.

Based on the electrochemical equilibrium condition established at the end of the open-circuit potential (OCP) test, cathodic polarization was performed to evaluate the behavior of the microstructures under hydrogen surface charging.

Fig. 4 shows the obtained cathodic polarization curve, where the characteristic hydrogen evolution region is clearly identifiable. It is observed that the sample in the as-received (CR) condition exhibited higher current density values in this region, suggesting increased cathodic activity.

This behavior may be associated with the specific microstructural features of this condition, namely the reduced interlamellar spacing, the presence of fragmented pearlite, and the higher grain deformation density resulting from the previous mechanical processing to which the material was subjected.

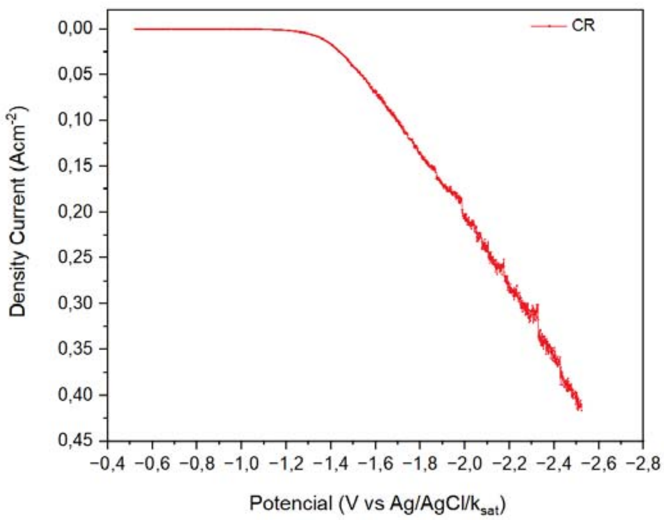

Fig. 4. Cathodic Polarization in 3.5% NaCl solution.

Based on the observed electrochemical characteristics, a cathodic potential of –2.0 V was adopted for the subsequent hydrogen charging tests, since this value lies within the region of high hydrogen fugacity. This condition was selected to enable a comparative evaluation of hydrogen embrittlement susceptibility in each microstructure.

With this potential established, the specimens were subjected to chronoamperometry for a period of 3 hours, promoting hydrogen diffusion into the material. Immediately after charging, uniaxial tensile tests were performed, and the results are presented in the following figures. In parallel, to establish a comparative baseline, identical tensile tests were conducted on samples not subjected to hydrogen charging, allowing proper characterization and assessment of the material's properties under standard conditions.

This methodological approach allowed for the precise quantification of hydrogen's influence on mechanical properties and the embrittlement phenomenon. Fig. 5 presents the stress–strain curves obtained for both conditions: without hydrogen charging and after 3 hours of charging at a fixed potential of –2.0 V.

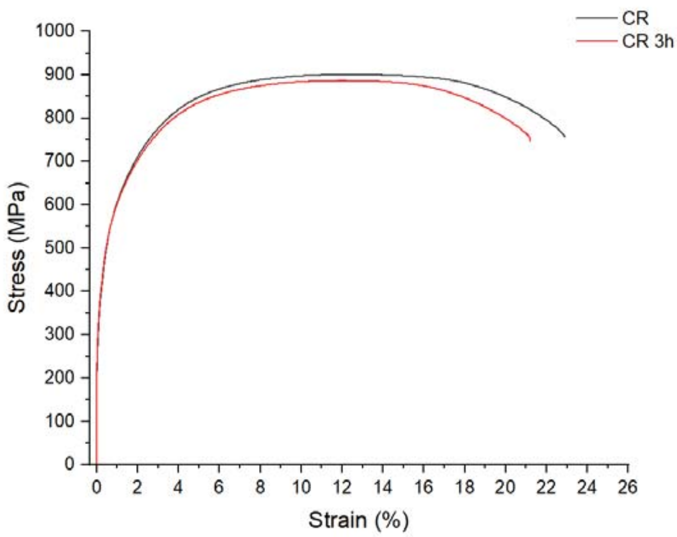

Fig. 5. Stress–Strain Diagram for As-Received (CR) and As-Received Material subjected to 3 h Hydrogen Charging (CR 3 h).

Based on the tensile test results presented in Fig. 5, a significant influence of hydrogen charging on the mechanical properties of the material in the as-received (CR) condition, which exhibits a fine pearlitic microstructure with fragmented cementite, can be observed.

The uncharged condition (CR) displayed a yield strength (YS) of approximately 630 MPa, a fracture stress (FS) of 850 MPa, and an elongation at fracture of 25%. After 3 hours of hydrogen charging at –2 V in 3.5% NaCl solution (CR 3 h), a reduction in ductility is observed, with elongation decreasing to approximately 21%. The yield strength decreased modestly to 610 MPa, while the fracture stress was significantly affected, dropping to 720 MPa.

This reduction in ductility and tensile strength can be attributed to the hydrogen embrittlement (HE) effect. The fine pearlitic microstructure with fragmented cementite, characteristic of the AR condition, presents a high density of ferrite/cementite interfaces and deformed grain boundaries. These microstructural features act as preferential sites for hydrogen atom trapping during cathodic charging.

The accumulation of hydrogen at these interfaces promotes crack nucleation and propagation, facilitating brittle fracture. The most likely embrittlement mechanism in this case is HELP (Hydrogen Enhanced Localized Plasticity), in which hydrogen locally reduces shear resistance, facilitating localized plastic deformation and subsequent microcrack nucleation. The significant reduction in elongation and fracture stress, with a smaller effect on yield strength, is consistent with this embrittlement mechanism [8].

These results demonstrate that even microstructures with fragmented cementite, which typically exhibit good mechanical strength, become highly susceptible to hydrogen embrittlement under cathodic charging conditions, with a drastic reduction in material toughness and deformation capacity.

CONCLUSION

The results obtained reinforce that the transition to low-carbon hydrogen-based energy systems cannot disregard a detailed analysis of the materials used in their infrastructure. Hydrogen embrittlement has proven to be a critical phenomenon, capable of significantly compromising the ductility and mechanical strength of pearlitic steels, highlighting that even alloys already established in strategic sectors may face severe limitations under this new application.

In this context, the importance of directing efforts toward understanding the degradation mechanisms induced by hydrogen, as well as developing mitigation strategies to adapt existing materials and infrastructures, becomes evident. The possibility of utilizing conventional transport networks, such as natural gas pipelines, represents a promising route to economically enable the energy transition. However, this alternative brings with it complex technical challenges, high adaptation costs, and additional risks related to operational safety.

Therefore, studies like the present one are essential for the design of new projects while also contributing to the assessment of the feasibility of repurposing existing structures. Overcoming these challenges will depend on the integration of advances in materials science, technological innovation, and infrastructure investment.

ACKNOWLEDGEMENTS

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COMPARANDO VEÍCULOS A HIDROGÊNIO VERDE E A ETANOL: O ESPAÇO OCUPADO PARA A PRODUÇÃO DE ENERGIA

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ABSTRACT

This work compares two renewable energy sources for vehicle movement, with the same kilometers traveled and in the same period of one year. The renewable sources are Ethanol and Green Hydrogen. Researching in the literature, analyzing the data and carrying out calculations, it is concluded that the space occupied by photovoltaic panels for Hydrogen production is approximately 2% of the area planted with sugar cane for ethanol production.

KEYWORDS
Green Hydrogen, Ethanol, Space Occupied for Power Generation.

ICTIM CARBON NEUTRAL: AN INSTITUTIONAL STRATEGY FOR CARBON OFFSET AND CLIMATE EDUCATION AS PUBLIC POLICY IN MARICÁ, BRAZIL

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ABSTRACT

In response to the worsening climate crisis and the increasing demand for concrete sustainability actions from public institutions, the ICTIM Carbon Neutral project was conceived as an institutional strategy to address environmental emergencies. The initiative focuses on mitigating and offsetting greenhouse gas (GHG) emissions resulting from the activities of the Maricá Institute of Science, Technology, and Innovation (ICTIM). The project's central objective is to promote carbon neutrality through a sustainable model that integrates measurement, offsetting, environmental education, and public engagement. To this end, the adopted methodology includes the preparation of a GHG emissions inventory using internationally recognized calculation tools. Emissions will be offset through the acquisition of carbon credits from certified projects, reforestation efforts, urban afforestation, and climate-focused environmental education initiatives. Continuous monitoring is planned, along with performance evaluation and the possibility of certification by specialized organizations. Expected results include a reduction in emissions in the municipality of Maricá, the expansion of green areas, the strengthening of sustainable practices, and the consolidation of a collective climate culture. The attainment of the "Carbon Neutral" seal will serve as institutional recognition and a stimulus for replication of the initiative. Currently underway, the project represents an innovative environmental public policy that combines technical rigor, social responsibility, and collective engagement. Its implementation aims to contribute to the construction of a more just, resilient, and low-carbon society.

KEYWORDS
Carbon Neutral, Public Policies, Environmental Education.

ANÁLISE E MITIGAÇÃO DE IMPACTOS RELACIONADOS À ALTA PENETRAÇÃO DE GERAÇÃO DISTRIBUÍDA EM REDES DE DISTRIBUIÇÃO ATRAVÉS DO SOFTWARE OPENDSS

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RESUMO

Os crescentes problemas de qualidade de energia associados à alta penetração da geração distribuída nas redes de distribuição das empresas de energia elétrica a cada dia estão necessitando maior atenção. A integração de sistemas de geração distribuída em grande escala, como os sistemas solares fotovoltaicos, criou desafios complexos na manutenção dos padrões de qualidade de energia. Este trabalho tem como objetivo principal investigar o escopo e a natureza desses problemas de qualidade de energia e desenvolver estratégias eficazes para mitigá-los. Serão realizadas análises abrangentes de vários aspectos da qualidade da energia, principalmente flutuações de tensão de longa duração, chamadas sobretensões. Para que se atinja o objetivo, o estudo inclui o monitoramento dos parâmetros de qualidade de energia em diversos pontos de uma rede de distribuição hipotética, baseada no alimentador teste de 13 nós IEEE. Uma análise detalhada dos indicadores de qualidade de energia afetados pela elevada penetração da geração distribuída é realizada para identificar áreas críticas onde estes problemas são mais recorrentes. A análise será feita no software OpenDSS, a partir dele é possível que sejam simulados sistemas de distribuição de energia elétrica de forma a se analisar no domínio do tempo as grandezas necessárias para o estudo proposto. Além disso, este trabalho irá fornecer e avaliar soluções práticas para melhorar a qualidade da energia na presença de múltiplos sistemas de geração distribuída. Isso inclui o desenvolvimento de tecnologias avançadas de controle de inversores e estratégias de coordenação entre unidades de geração distribuída e as concessionárias de energia.

PALAVRAS-CHAVE
Geração Distribuída; Qualidade de Energia; Rede de Distribuição; OpenDSS.

INTRODUÇÃO

Cada vez mais busca-se sustentabilidade no Brasil e no mundo, principalmente no que tange à geração de energia elétrica, com a crescente penetração de fontes renováveis, em especial a solar fotovoltaica, na rede de distribuição. A crise hídrica de 2021, provocada pela pior seca em 91 anos, reduziu os reservatórios das hidrelétricas responsáveis por cerca de 70% da energia hidráulica nacional, resultando em aumento abrupto do preço da energia e reforçando a necessidade de diversificação da matriz elétrica[1], [2]. Nesse contexto, a energia solar fotovoltaica destaca-se como alternativa sustentável, com crescimento acelerado da capacidade instalada no país[3].

A geração solar pode ser realizada de forma distribuída (GD) ou centralizada. No caso da GD, as resoluções da ANEEL estabeleceram a distinção entre micro e minigeração, normalmente associadas a telhados residenciais, comércios e pequenas indústrias, enquanto a geração centralizada ocorre em usinas de grande porte[4]. A Lei 14.300/2022 consolidou o marco legal da micro e minigeração distribuída, trazendo mudanças no Sistema de Compensação de Energia Elétrica (SCEE). Apesar da expectativa de retração, a queda nos preços de módulos fotovoltaicos tem impulsionado a expansão da GD no Brasil[5].

Por outro lado, os alimentadores de distribuição foram projetados para fluxos unidirecionais de potência, o que torna crítica a presença de altas penetrações de GD, sobretudo em baixa e média tensão. Entre os principais problemas, destaca-se a regulação de tensão e a ocorrência de sobretensões em cenários de elevada geração e baixo consumo[6]. Diversos autores vêm analisando esse fenômeno. Kishor et al.[7] identificaram limite de penetração de 40% no sistema IEEE 13 nós, que poderia ser ampliado com suporte reativo. Aziz[8] mostrou que redes mais robustas podem suportar até 90% de penetração. Outros trabalhos [9] exploraram o uso de bancos de reatores, baterias e estratégias de suporte reativo como alternativas técnicas.

Entre as soluções destacam-se os controles inteligentes de potência reativa incorporados em inversores, conhecidos como Volt-Var. Pesquisadores como Sun et al.[10], Jabr[11] e Xiong et al.[12] demonstraram que o uso coordenado dessa estratégia é eficaz na mitigação de sobretensões e na redução de perdas. No Brasil, o PRODIST da ANEEL (Módulo 8)[13] e as normas ABNT NBR 16149:2013[14] e 16274:2014[15] já regulamentam a utilização da função Volt-Var em inversores, permitindo sua operação automática. No entanto, sua adoção prática ainda é limitada por não ser obrigatória em grande parte dos projetos, pela ausência de incentivos regulatórios e pela possibilidade de redução na injeção de potência ativa.

Casos recentes, como a negativa de acesso de novos sistemas de GD em redes da CEMIG [16], evidenciam que os métodos convencionais de conexão não são suficientes diante da alta penetração fotovoltaica. Diante desse cenário, torna-se relevante analisar os impactos e benefícios da aplicação do controle Volt-Var em redes de distribuição com elevada participação da geração solar.

Neste trabalho, a análise é conduzida em uma rede padrão IEEE de 13 nós, amplamente utilizada em estudos acadêmicos, adaptada à realidade brasileira. Foram considerados perfis típicos de carga e curvas de geração solar, de modo a avaliar o desempenho do Volt-Var em diferentes cenários de penetração fotovoltaica. O objetivo é verificar a contribuição desse controle para mitigar sobretensões, melhorar o perfil de tensão e aumentar a resiliência da rede frente às variações de carga e geração.

METODOLOGIA

Estudo de caso

Neste trabalho foi adotado o alimentador IEEE de 13 nós como sistema de referência. Esse circuito é amplamente utilizado na literatura por representar de forma adequada as condições de operação de redes reais de distribuição, com presença de linhas desequilibradas, transformadores, reguladores de tensão e cargas de diferentes tipologias (residenciais, comerciais e industriais).

O alimentador utilizado está representado na Fig. 1.

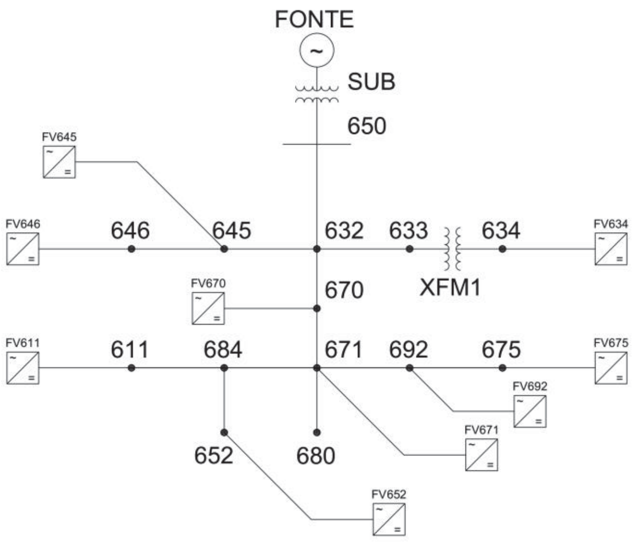


Fig. 1. - Diagrama do alimentador padrão IEEE de 13 nós com a presença das GD's.

A geração fotovoltaica foi conectada em múltiplos pontos do alimentador IEEE de 13 nós, abrangendo barras de baixa e média tensão: 611, 634, 645, 646, 652, 670, 671, 675 e 692, conforme ilustrado na **Erro! Fonte de referência não encontrada.**

Apesar da presença de geração em diferentes nós, a análise detalhada concentrou-se em três barramentos representativos: a 634, de baixa tensão; a 645, localizada próxima à subestação e utilizada como referência; e a 671, situada em região mais distante do alimentador, onde os impactos de tensão tendem a ser mais acentuados.

Configuração das simulações

As simulações foram realizadas no software OpenDSS, em modo diário, com passo horário de 1 hora (24 etapas). Foram considerados perfis de carga típicos para consumidores residenciais, comerciais e industriais, bem como uma curva horária de geração solar fotovoltaica.

O fluxo utilizado como metodologia para as simulações está descrito na Fig. 2.

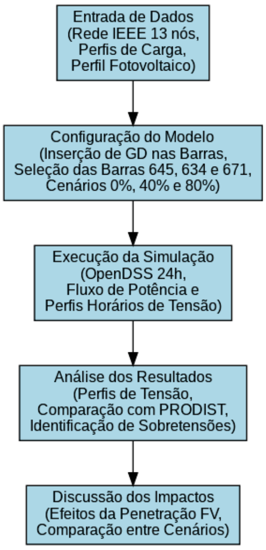
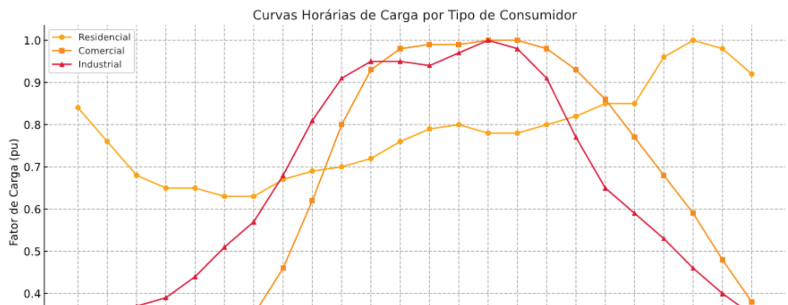
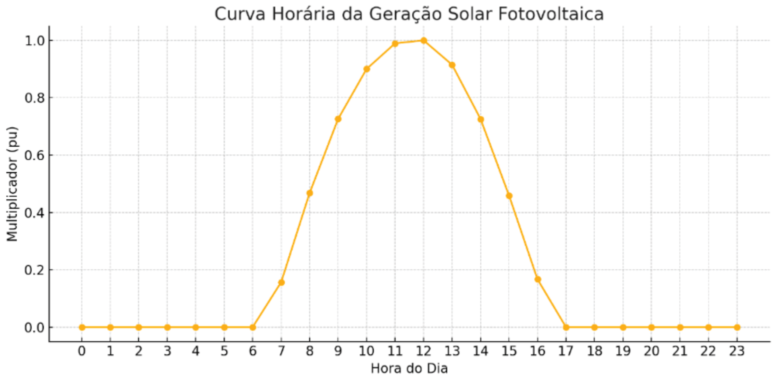


Fig. 2. - Fluxograma do processo de simulação no OpenDSS

Foram definidos três cenários de penetração de geração distribuída. No primeiro caso, correspondente a 0% de penetração, o sistema operou apenas com as cargas originais, sem a presença de geração fotovoltaica. No segundo caso, a penetração foi ajustada para 40% da demanda total, condição em que a geração fotovoltaica já exerce impacto expressivo sobre o perfil de tensão, podendo provocar elevações relevantes em determinados períodos do dia, ainda que com menor intensidade de exportação de potência ativa para a rede. Por fim, no terceiro caso, a penetração atingiu 80% da demanda, ampliando de forma acentuada a injeção de potência ativa, o que resulta em fluxos reversos mais frequentes e na ocorrência de sobretensões ao longo do alimentador.
Foram modeladas três curvas típicas para consumidores residenciais, comerciais e industriais, com 24 pontos representando cada hora do dia.



A operação seguiu a curva horária de geração, reproduzindo a variação de irradiância ao longo do dia e permitindo comparar os impactos da geração distribuída nos perfis de tensão para diferentes níveis de penetração.



Cálculo da penetração fotovoltaica

Para dimensionar a potência nominal de cada gerador fotovoltaico, foi adotado como referência um cenário hipotético de 100% de penetração, no qual a energia gerada em 24 horas seria igual à energia total consumida no mesmo intervalo. Este cenário não fez parte da análise de resultados, sendo utilizado exclusivamente para o cálculo da capacidade instalada dos geradores fotovoltaicos.

A energia consumida foi determinada por:

$$Econsumida = \sum_{\ell \in cargas} P\ell \left(\sum_{h=1}^{24} m_{t(\ell),h}\right) \Delta t$$

onde:

- $P\ell$ é a potência ativa nominal da carga ℓ (kW);
- $m_{t(\ell),h}$ é o multiplicador horário (pu) do perfil de carga do tipo $t(\ell)$ (residencial, comercial ou industrial) na hora h, esse multiplicador é obtido a partir das curvas de consumo expostas anteriormente;
- Δt é o intervalo de tempo (1 h);
- $Econsumida$ é a energia consumida em 24 h (kWh).

Com a energia total consumida (Econsumida) e o somatório dos multiplicadores do perfil solar (∑Irprf1), calculou-se a potência nominal necessária para o cenário hipotético de 100% de penetração, conforme:

$$Pmpp = \frac{Econsumida}{\sum Irprf1}$$

onde:

- $\sum Irprf1$ representa o somatório dos multiplicadores do perfil solar, é obtido a partir da curva solar exposta anteriormente;
- $Pmpp$ é a potência nominal do sistema fotovoltaico (kW) para 100% de penetração.

Os cenários efetivamente simulados variaram a irradiância nominal de todos os sistemas fotovoltaicos proporcionalmente, representando diferentes níveis de penetração de geração distribuída, inferiores a 100%, para avaliar de forma comparativa seus impactos na rede de distribuição.

Por exemplo, para se obter 80% de penetração temos:

$$Pmpp_{80\%} = 0,8\ x\ Pmpp$$

RESULTADOS

Nesta seção são apresentados os resultados das simulações realizadas. A análise contempla a variação dos perfis de tensão nas diferentes barras do sistema, destacando os impactos provocados pela inserção da geração distribuída (GD) em distintos níveis de penetração. São evidenciadas as flutuações de tensão e identificados os pontos mais críticos em relação à qualidade de energia, incluindo os casos em que ocorreram violações dos limites estabelecidos pelo PRODIST. Em seguida, são discutidos os efeitos da aplicação da estratégia de controle Volt-VAR nos inversores fotovoltaicos, demonstrando sua contribuição para a mitigação das sobretensões e para a manutenção das tensões dentro da faixa adequada de operação. Dessa forma, os resultados permitem comparar cenários com e sem controle, fornecendo subsídios técnicos para a integração mais segura e eficiente da GD às redes de distribuição.

Para melhor ilustrar a análise desenvolvida, foram selecionados alguns pontos representativos do sistema. As Figuras 3 a 5 mostram os perfis de tensão nas barras 634, 645 e 671 (fase B), comparando o cenário 5 com e sem o controle proposto. Observa-se que, em determinados intervalos, a operação sem controle provoca elevações significativas de tensão, ultrapassando os limites regulamentares. Com a estratégia de compensação reativa, essas sobretensões são atenuadas e as tensões permanecem dentro da faixa aceitável de operação. A comparação direta evidencia a efetividade do controle, demonstrando sua contribuição para a melhoria da qualidade de energia e para a confiabilidade da rede frente à inserção da GD.

Resultados

- Comparação barra 634 – Fase B (cenário 5)

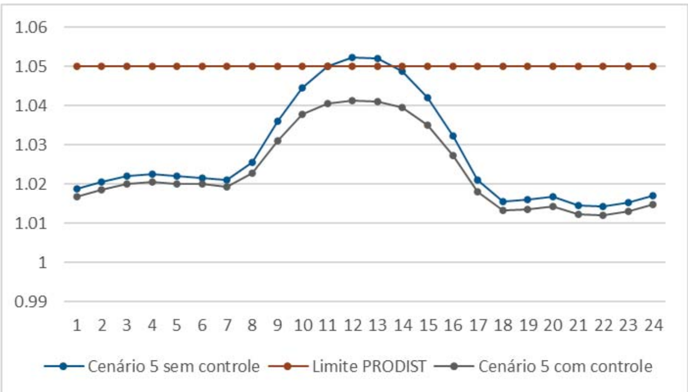


Fig. 3. – Barra 634 – Fase B (PU) – Comparação

Na barra 634, sem controle a tensão chega a 1,05 pu, ultrapassando ligeiramente o limite do PRODIST. Com o controle aplicado, o pico cai para cerca de 1,04 pu, mantendo a tensão dentro da faixa regulamentar durante todo o período.

- Comparação barra 645 – Fase B (cenário 5)

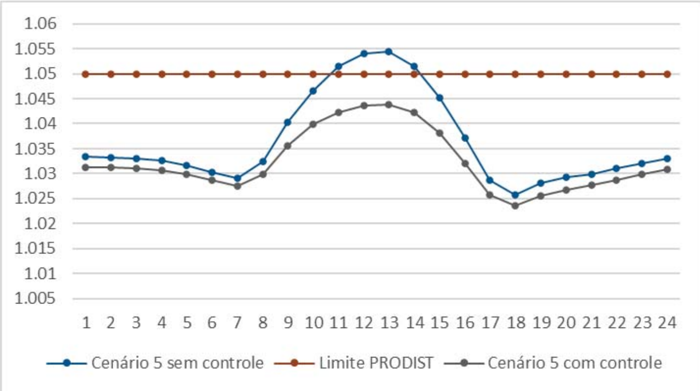


Fig. 4. - Barra 645 – Fase B (PU) - Comparação

Na barra 645, a condição sem controle apresenta pico em torno de 1,06 pu, acima do limite permitido. Com o controle, o valor máximo se reduz para aproximadamente 1,04 pu, evidenciando a efetividade da estratégia em mitigar as sobretensões.

- Comparação barra 671 – Fase B (cenário 5)

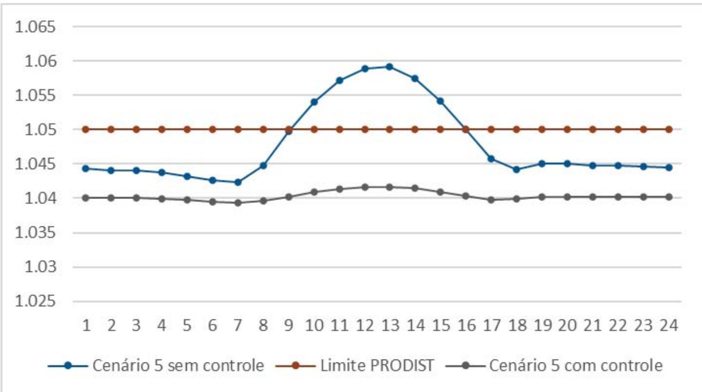


Fig. 5. - Barra 671 – Fase B (PU) - Comparação

Na barra 671, o cenário sem controle registra pico próximo de 1,06 pu, caracterizando violação significativa. Já com o controle, a máxima tensão observada fica em torno de 1,04 pu, o que elimina as ultrapassagens e assegura a conformidade normativa.

Análise dos resultados obtidos

Com o objetivo de compreender os impactos da geração distribuída fotovoltaica sobre os níveis de tensão do sistema IEEE 13 nós, foi realizada uma análise comparativa dos perfis de tensão nas barras 634, 645 e 671, considerando os cenários com e sem a aplicação da estratégia de controle Volt-VAR. A investigação buscou identificar os pontos mais sensíveis às variações de tensão, especialmente aqueles em que os valores ultrapassaram o limite superior de 1,05 pu estabelecido pelo PRODIST.

As extrapolações ocorreram na barra 634 e na barra 645 no cenário 3 (80% de penetração), enquanto na barra 671 as violações foram observadas já no cenário 2 (40%), intensificando-se no cenário 3. Essas barras foram selecionadas como foco da análise por representarem situações críticas para a operação do sistema em condições de alta penetração fotovoltaica.

A comparação entre os resultados com e sem controle fornece subsídios para verificar a efetividade do Volt-VAR na mitigação das sobretensões e para compreender como os impactos se propagam por diferentes barras e fases do sistema.

Caso o controle Volt-VAR fosse realizado apenas por um único gerador fotovoltaico, haveria maior esforço individual de potência reativa. Isso faria com que o inversor operasse mais próximo do seu limite de capacidade e com fator de potência reduzido. Nessa condição, o FP poderia “afundar” para valores inferiores a 0,95, comprometendo a eficiência e a conformidade normativa. Já com a atuação distribuída entre todos os inversores, a demanda de reativos é compartilhada, mantendo fatores de potência próximos à unidade e sem sobrecarga individual.

Para viabilizar essa comparação do desempenho, especialmente em relação ao fator de potência, a curva Volt-VAR foi ajustada de forma a abranger a faixa de operação mais crítica em baixa tensão (até 1 kV). A nova parametrização adotada considerou quatro pontos de operação, definidos pelas coordenadas de tensão e potência reativa: (0,92 pu; +0,44 pu), (0,99 pu; 0), (1,01 pu; 0) e (1,05 pu; –0,44 pu). Dessa forma, a curva passou a representar uma banda mais estreita em torno da tensão nominal, permitindo avaliar com maior precisão como o fator de potência dos inversores é impactado sob condições de afundamento ou elevação de tensão.

A análise foi realizada em duas etapas: inicialmente, mantendo o controle de tensão apenas no ponto de geração da barra 634; em seguida, distribuindo o controle para todos os pontos de geração ao longo do alimentador.

A Tabela 1 apresenta a comparação entre essas duas situações, destacando as diferenças observadas no fator de potência, tanto em termos de esforço individual de potência reativa quanto da operação conjunta mais equilibrada.

Tabela 1 - Comparação do fator de potência

hora	P (kW)	Q (kvar - 634)	FP (634)	Q (kvar - Todas)	FP (Todas)
8	-48.0451	36.3511	0.797465	0.865025	0.999838
9	-143.49	59.7229	0.923224	20.511	0.989937
10	-222.666	75.2196	0.947402	34.9433	0.987909
11	-276.145	82.0171	0.958612	42.078	0.988589
12	-303.497	82.8204	0.964725	44.3369	0.989497
13	-306.729	82.3952	0.965762	44.4437	0.989665
14	-280.674	79.281	0.962435	39.7976	0.990096
15	-222.608	70.7195	0.953062	28.9756	0.991635
16	-140.767	52.1066	0.937812	10.9732	0.996975
17	-51.137	26.9666	0.884544	2.75298	0.998554

CONCLUSÃO

A análise dos perfis horários de tensão nas barras da rede modelada, evidenciou variações relevantes no comportamento das tensões ao longo do dia em função da alta penetração de geração distribuída (GD). Em todos os cenários simulados, verificou-se aumento de tensão em todas as barras analisadas, sendo que, em algumas fases de determinadas barras, houve extrapolação do limite de sobretensão estabelecido pelo PRODIST, fazendo com que a tensão saísse da faixa adequada.

Observou-se que, à medida que o nível de penetração aumentou, as tensões se aproximaram dos limites superiores normativos, com violações mais evidentes nos horários de pico de geração. Essas variações reforçam a necessidade de mecanismos de controle capazes de atuar dinamicamente para manter a qualidade da energia dentro dos padrões técnicos.

A inserção do controle Volt-VAR nos inversores fotovoltaicos demonstrou que, quando devidamente dimensionado, esse recurso contribui de forma significativa para a mitigação das sobretensões associadas à alta penetração de GD. O controle Volt-VAR foi capaz de suavizar picos e manter o perfil de tensão ao longo do alimentador, reduzindo o risco de violações de limite.

Os resultados obtidos permitem concluir que, para a integração segura e eficiente de geração distribuída em redes de distribuição, é fundamental considerar a aplicação de estratégias de controle como o Volt-VAR, aliadas a um planejamento criterioso da localização e dimensionamento das unidades geradoras. Dessa forma, é possível ampliar a participação da GD no sistema elétrico sem comprometer a qualidade e a confiabilidade do fornecimento.

AGRADECIMENTOS

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A STUDY OF MANUFACTURING SCALABILITY FOR SUPERCAPACITORS USING GRAPHENE OXIDE AND A SEQUENTIAL HTC ACTIVATION PROCESS

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ABSTRACT

The growing interest in activated carbon (AC) stems from its broad applications in environmental remediation and energy storage. Integrating graphene oxide with food waste-derived precursors enhances AC's surface area, porosity, and chemical functionality, key for efficient water purification, gas adsorption, and electrochemical systems.

AC is typically produced through thermal processes such as physical or chemical activation, which allow precise control of material properties based on feedstock and process parameters. This flexibility enables the design of carbon materials tailored for specific applications.

This study explores the production of AC from graphene oxide and food waste-based compounds; specifically cellulose, chitosan, and brewer's spent grains by using a two-step process. Hydrothermal carbonization (HTC) was performed at 240°C for 2 hours, followed by steam-assisted activation at 750°C for 30 minutes. Water steam was selected as an environmentally friendly and efficient activating agent for pore formation.

The resulting materials underwent comprehensive characterization by Raman spectroscopy, SEM-EDX, FTIR, pH analysis, BET surface area measurement, and thermal stability tests to assess their structural and chemical evolution. Yields and nitrogen retention were measured under varying input conditions.

Results showed significant nitrogen retention even without graphene oxide. Raman spectra confirmed that steam activation removes volatiles and promotes formation of more ordered carbon structures. SEM revealed that non-activated hydrochars contained carbon microspheres and fragments with low porosity, whereas activated samples exhibited cracked, heterogeneous surfaces and well-developed pore networks formed during steam activation.

This study provides insights into scalable production of high-performance AC from food waste and graphene oxide. It demonstrates the potential of coupling hydrothermal carbonization with environmentally benign activation strategies to generate advanced carbon materials for sustainable energy and environmental applications.

KEYWORDS
Activated carbon, hydrothermal carbonization, pyrolysis

Effect of the initial inorganic composition of the feedstock in the biochar production for soil amendment

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ABSTRACT

Biochar has attracted considerable attention in recent years, mainly because of its potential environmental and agricultural benefits when applied to soil. These benefits include improved nutrient and water retention, increased soil organic matter, improved agricultural productivity, simultaneously contributing to carbon sequestration and the reduction of soil-borne greenhouse gas emissions. Biochar is commonly produced by slow pyrolysis and its properties can be significantly altered depending on the initial feedstock, the conversion process, and the application of pre- and post-treatments [1]. This flexibility allows for tailored engineering of biochar to meet specific application-oriented production goals.

The primary focus of this study is to experimentally investigate the effect of slow pyrolysis process conditions, including temperature (350, 425 and 500 °C), residence time (1 and 3h), as well as the initial feedstocks with low and high ash content (Miscanthus, Hemp stalks and Grass silage). The relevant biochar physicochemical properties such as elemental analysis, pH, specific surface area inorganic composition and thermal stability were measured. Product yields under different conditions are compared to provide a global view of the process.

Inorganic species have the potential to modify chemical reactions during the pyrolysis [2], resulting in a higher degree of aromatization (lower H/C and O/C ratios between 0.49-1.72 and 0.04-0.6 respectively) and improved thermal stability. Higher temperatures during pyrolysis contribute to shorter residence times and lower volatile matter in the biochar [3]. This in turn reduces the occurrence of intra-particle secondary reactions and the recondensation of both organic and inorganic species. Consequently, the variations in the pyrolysis conditions does indeed influence the physical and chemical structure of the resulting biochar.

KEYWORDS
Biochar, soil amendment, inorganic compounds

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THE POTENTIAL OF AGRIVOLTAIC SYSTEMS FOR THE ENERGY TRANSITION IN PORTUGAL

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ABSTRACT

Portugal's transition toward carbon neutrality strongly depends on the expansion of photovoltaic (PV) energy, an essential driver for decarbonization and for meeting national and European climate goals. This study examines the role of agricultural areas in southern Portugal in the energy transition, highlighting their high solar potential and coexistence with extensive farmland. Through the analysis of solar irradiation and land-use data, a strategic opportunity is identified for the adoption of agrivoltaic systems (APV), which can promote efficient land use. The findings suggest that APV systems can contribute to territorial cohesion, rural development, and food security while accelerating Portugal's energy transition toward carbon neutrality.

KEYWORDS
Agrivoltaic systems, carbon neutrality, land use.

INOVAÇÃO ENERGÉTICA E SUSTENTABILIDADE URBANA: HIDROGÊNIO BAIXO TEOR DE CARBONO NO CONTEXTO DO TRANSPORTE COLETIVO

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RESUMO

O setor de transporte urbano é responsável por significativa parcela das emissões de gases de efeito estufa no Brasil, impactando negativamente o meio ambiente, a sociedade e a economia. A crescente demanda por mobilidade confirma a necessidade de soluções sustentáveis, que integrem eficiência energética, redução de poluentes e inclusão social. Nesse contexto, o hidrogênio emerge como vetor energético promissor, produzido a partir de fontes renováveis, capaz de fornecer energia limpa e de alta densidade para sistemas de transporte público. No presente estudo, busca-se analisar o potencial do hidrogênio como alternativa sustentável no transporte coletivo urbano, considerando aspectos ambientais, sociais, econômicos e tecnológicos. Para tanto, adotou-se metodologia indutiva, com abordagem qualitativa, caracterizada como pesquisa descritiva e estudo de caso. A pesquisa baseou-se em revisão bibliográfica de fontes acadêmicas e institucionais, análise de dados sobre mobilidade urbana e transporte sustentável, bem como no acompanhamento de projetos e iniciativas de implementação de ônibus a hidrogênio em contextos urbanos brasileiros. A partir dos resultados, acredita-se que a utilização de hidrogênio em veículos híbridos ou exclusivamente movidos a células de combustível pode reduzir significativamente emissões de gás carbônico, melhorar a eficiência energética das frotas e reduzir custos operacionais a longo prazo. Nessa perspectiva, conclui-se que o hidrogênio baixo teor de carbono constitui alternativa viável e estratégica, e a integração de políticas públicas, parcerias público-privadas e investimentos em pesquisa e desenvolvimento devem consolidar seu uso no transporte coletivo, em prol da sustentabilidade.

PALAVRAS-CHAVE
Hidrogênio baixo teor de carbono, Mobilidade urbana, Transporte sustentável, Inovação tecnológica.

INTRODUÇÃO

Nos últimos anos, a crescente demanda por transporte no Brasil tem impulsionado o consumo de combustíveis fósseis, ocasionando aumento significativo das emissões de gases de efeito estufa, com impactos adversos tanto para a população quanto para os ecossistemas, sendo o setor de transporte responsável pela maior parcela dessas emissões no país [1].

Considerando a relevância de estratégias e boas práticas, no presente estudo, busca-se discutir a transição para uma mobilidade urbana mais sustentável, alinhada aos imperativos ambientais, sociais e econômicos contemporâneos.

A sustentabilidade se apoia em três pilares interrelacionados: o ambiental, que promove o uso de energia limpa, a redução de resíduos, a economia de recursos, a mitigação de mudanças climáticas e a preservação de áreas naturais; o social, que assegura igualdade de acesso, melhora a saúde e a qualidade de vida da população, fomenta o desenvolvimento econômico, preserva a herança cultural e garante segurança; e o econômico, que prioriza a viabilidade financeira, a eficiência, a indução ao desenvolvimento econômico e a redução de custos de implantação e operação [2].

Frente à influência dos sistemas de transporte sobre o meio ambiente, a sociedade e a economia, a mobilidade sustentável visa integrar questões como poluição do ar, acessibilidade, mobilidade de baixa renda e transporte de bens e serviços, sendo imprescindível que sua gestão seja participativa, democrática e articulada com políticas urbanas integradas, a fim de garantir acesso eficiente a bens e serviços sem comprometer a qualidade de vida das gerações futuras. Nesse contexto, tem-se a inserção do hidrogênio como vetor energético de baixo carbono para transporte urbano, oferecendo potencial para reduzir emissões, diversificar a matriz energética e fomentar inovação tecnológica.

O conteúdo deste artigo foi desenvolvido no âmbito da Encomenda Tecnológica (ETEC) e do Projeto de Pesquisa em Desenvolvimento e Inovação (PDI), conduzidos pelo Instituto de Ciência, Tecnologia e Inovação de Maricá (ICTIM), cuja missão institucional envolve a realização de pesquisas científicas e tecnológicas, desenvolvimento de novos produtos, serviços e processos, bem como a promoção da ciência, tecnologia, inovação e cultura na cidade de Maricá, com especial atenção à implementação de soluções sustentáveis no transporte público urbano.

FUNDAMENTAÇÃO TEÓRICA

O desafio global consiste em reduzir as emissões de gases de efeito estufa em 7,6% ao ano entre 2021 e 2030. Conforme o *World Energy Outlook* 2021 da Agência Internacional de Energia (IEA), estima-se a necessidade de eliminar cerca de 14 bilhões de toneladas de CO_2 até 2030 para limitar o aumento da temperatura média global a 1,5°C. No entanto, o não cumprimento das metas nacionais indica uma trajetória de aquecimento de aproximadamente 2,7°C [1].

A avaliação de viabilidade de novos projetos busca analisar se produtos ou serviços propostos são sustentáveis, considerando metas estratégicas e impactos ambientais, sociais e econômicos. Assim, reflete-se sobre a análise logística e das demandas reais da população, a fim de mensurar a viabilidade de sistemas de transporte que utilizem combustíveis alternativos. Nesse contexto, o foco deve recair sobre práticas de sustentabilidade, eficiência energética, utilização de fontes renováveis e inovação tecnológica, principalmente na adoção de veículos elétricos, que apresentam zero emissão direta de CO_2, menor custo de manutenção, baixo ruído e eficiência operacional superior [4].

No Brasil, fabricantes de chassis de ônibus, em parceria com encarroçadoras nacionais, disponibilizaram veículos elétricos para o transporte urbano em grandes centros, demonstrando o potencial estratégico e ambiental dessa tecnologia [3].

Hidrogênio baixo teor de carbono

O hidrogênio tem se consolidado como vetor energético relevante para a neutralidade de carbono, podendo ser convertido em eletricidade ou combustíveis sintéticos para fins industriais, comerciais e de mobilidade urbana. Trata-se de um gás abundante, incolor, inodoro, insípido e não tóxico. O desenvolvimento tecnológico do hidrogênio engloba toda a cadeia de produção, armazenamento, transporte, distribuição e utilização final [4].

No setor de transporte, apresenta elevada energia específica (120 MJ/kg) e alto rendimento energético, aproximadamente 2,5 vezes superior aos combustíveis fósseis convencionais. Integrado a sistemas híbridos elétrico-hidrogênio, permite tração eficiente de veículos com emissão de vapor d’água como subproduto, representando significativa vantagem ambiental [5].

Projetos-piloto na América Latina demonstram o potencial do hidrogênio baixo teor de carbono no transporte público: na Argentina, abastecendo ônibus em Buenos Aires; no Paraguai, aproveitando excedentes hídricos e elétricos; e no Uruguai, testando veículos pesados e promovendo o “Dia do Hidrogênio” [6]. No Brasil, o Plano Nacional de Energia 2050 estabelece diretrizes para regulamentação e implantação de tecnologias disruptivas, incluindo o hidrogênio.

Nessa perspectiva, propõe-se a substituição de ônibus a diesel por veículos com células de combustível a hidrogênio na cidade de Fortaleza, sustentadas por energia eólica, estimando uma geração anual de 766,93 GWh para atender à demanda energética do sistema. Para tanto, dimensionou-se um parque eólico com capacidade de 840 GWh anuais, considerando perdas e consumo de estações de reabastecimento. Do total energético, 54,75% seriam convertidos em hidrogênio, 41,93% cobririam perdas do sistema e 3,32% destinariam-se a estações de abastecimento e compressão [4].

Assim, o hidrogênio representa alternativa promissora para diversificação da matriz energética brasileira, especialmente se sua produção utilizar fontes renováveis ou tecnologias de captura e utilização de CO_2. Ressalta-se que padrões tecnológicos e dinâmica global da cadeia produtiva ainda se consolidam, sendo a competitividade nacional dependente da formação de competências locais [10]. Portanto, há a necessidade de desenvolvimento de capacidades inovativas em veículos, sistemas e componentes para sustentar a competitividade da indústria automotiva.

A legislação brasileira aponta para uma transição gradual na matriz energética do transporte público. Apesar do avanço na produção de biodiesel e etanol, muitas empresas optaram pela eletrificação da frota, considerando vantagens econômicas e operacionais. No entanto, essa escolha exige investimentos significativos em infraestrutura urbana, configurando um dilema entre setor público e privado quanto à melhor alternativa energética [11].

METODOLOGIA

Neste artigo, adota-se o método indutivo, por fornecer bases lógicas à investigação a partir da observação da realidade concreta, sem pressupor princípios preestabelecidos [7], em que a generalização resulta da análise de casos observados.

Sob essa perspectiva, a pesquisa é conduzida de forma sistemática e formal, com o objetivo de solucionar problemas mediante procedimentos científicos [7]. Caracteriza-se como pesquisa descritiva, uma vez que envolve o registro e a análise das características do fenômeno em estudo, minimizando a interferência do pesquisador por meio de técnicas padronizadas de coleta e análise de dados, tendo como foco a utilização de energias alternativas no transporte urbano e sua contribuição para a redução da poluição atmosférica e aprimoramento do desempenho operacional das empresas do setor.

A abordagem é qualitativa, buscando compreender os fenômenos a partir da explicação de seus determinantes e atribuindo significados às observações, considerando subjetividades e nuances frequentemente não quantificáveis, como experiências relacionadas a testes de combustíveis e tecnologias alternativas.

Os procedimentos adotados incluem pesquisa bibliográfica, baseada em material previamente publicado, como livros, artigos científicos e fontes digitais [8], ressaltando esse tipo de estudo como levantamento abrangente do conhecimento já existente [9].

RESULTADOS E DISCUSSÃO

Os dados de pesquisa foram extraídos de relatórios de acompanhamentos mensais da cidade de Maricá (RJ), e fornecem embasamento para entender a dinâmica do serviço de transporte público e suas demandas diárias.

A análise de custos é um importante componente da avaliação, abrangendo custos de veículos com baterias, instalação de infraestrutura de carregamento, carregamento, manutenção, substituição e custos de pessoal. Além disso, foram considerados os benefícios ambientais, incluindo economia de energia, redução nas emissões de gases de efeito estufa e poluentes.

Desse modo, seria possível avaliar o impacto positivo que a adoção de ônibus elétricos pode ter no meio ambiente e na qualidade do ar, contribuindo para uma compreensão mais completa e contextualizada da transição para ônibus elétricos no transporte público.

Formulários de acompanhamento de projetos

No âmbito do Projeto de Mobilidade Inteligente pelo Desenvolvimento Orientado do Transporte Sustentável, foram registrados, entre fevereiro e novembro de 2023, avanços significativos no estudo do hidrogênio como vetor energético para o transporte público urbano em Maricá (RJ) [2]. Em fevereiro, os trabalhos focaram na construção do referencial teórico e na inclusão do hidrogênio na mobilidade urbana, destacando a complexidade territorial do município e o potencial do Brasil no desenvolvimento de ônibus elétricos híbridos a hidrogênio, assim como a necessidade de colaboração entre os setores público e privado e de investimentos governamentais em hidrogênio de baixo carbono.

Em março, o relatório abordou projetos-piloto de ônibus híbridos, assinalando a importância de planejamento de infraestrutura, tipos de carregamento, rotas, treinamento das equipes e definição de objetivos de desempenho, incluindo autonomia, políticas de apoio, suporte operacional, redução de emissões e custeio adequado. Destacou-se que tais projetos seriam iniciados em 2024, permitindo testar infraestrutura, capacitar equipes e coletar dados estratégicos para futuras expansões [10].

Em abril, observou-se crescente adoção de ônibus sustentáveis, motivada pela redução das emissões de gases de efeito estufa e pelo interesse em transporte público de baixa emissão, considerando que 42,1% da população depende desse serviço. O relatório apresentou avanços tecnológicos e oportunidades de financiamento, bem como a necessidade de contratos detalhados e estratégias de interoperabilidade da infraestrutura de recarga.

Em maio, foram discutidos desafios e oportunidades financeiras da transição para ônibus híbridos elétrico-hidrogênio, com destaque para o Custo Total de Propriedade (TCO) e mecanismos de custeio, incluindo financiamento de dívida, leasing de baterias e compras conjuntas, reconhecendo a importância de subsídios e incentivos governamentais.

No mês seguinte (junho), observou-se a adaptação operacional para a substituição de ônibus a diesel, com atenção à autonomia, planejamento de rotas, desempenho das baterias e infraestrutura de recarga, buscando confiabilidade e eficiência de custos.

Em julho, os relatórios ressaltaram que a simples eletrificação não é suficiente, sendo necessária integração com políticas de emissão zero, redução de tráfego, eletrificação da rede elétrica, planejamento urbano e integração multimodal do transporte público. Os indicadores avaliados incluíram capacidade de passageiros, eficiência operacional, taxa de substituição e desempenho da infraestrutura de carregamento [9].

Em agosto, a pesquisa sobre a viabilidade do hidrogênio no transporte urbano reforçou seu potencial estratégico, desafios tecnológicos e econômicos, importância de parcerias público-privadas, investimentos em P&D, o papel do Plano Nacional de Hidrogênio (PNH2) e a relevância das tecnologias CCUS, com análise comparativa de custos entre hidrogênio azul e gás natural [11].

Em setembro, foram realizadas visitas técnicas à fábrica da Tracel e estudos sobre a substituição gradual da frota a diesel por veículos a hidrogênio, mencionando benefícios ambientais, sociais e econômicos, bem como a necessidade de investimentos em inovação e infraestrutura.

Em outubro, os relatórios abordaram a produção de hidrogênio em Maricá, incluindo rotas verdes e a partir de gás natural, avultando seu papel na descarbonização da economia, alinhamento com metas do Acordo de Paris, oportunidades no transporte, geração elétrica e armazenamento de energia, e a necessidade de regulamentação, certificação ambiental e superação de desafios tecnológicos e logísticos [9].

Por fim, em novembro, ressaltou-se o potencial do hidrogênio como fonte energética abundante e sustentável, com projeções globais de demanda até 2050, aplicabilidade no transporte, na indústria e como matéria-prima limpa, avigorando a posição estratégica do Brasil no desenvolvimento da economia do hidrogênio [12].

CONSIDERAÇÕES FINAIS

A partir da análise realizada, conclui-se que a transição para uma mobilidade urbana sustentável representa certa complexidade, por envolver dimensões ambientais, sociais e econômicas interdependentes. O setor de transporte, responsável por grande parcela das emissões de gases de efeito estufa, demanda soluções que conciliem eficiência operacional, redução de impactos ambientais e promoção da equidade social, especialmente no acesso de populações de baixa renda aos serviços urbanos.

Isso posto, considera-se que a adoção do hidrogênio como vetor energético configura alternativa promissora, oferecendo elevado rendimento energético, baixo impacto ambiental e potencial para integrar sistemas híbridos de propulsão, contribuindo para a descarbonização do transporte coletivo urbano. Estudos recentes ([4]; [5]) indicam que, quando produzido a partir de fontes renováveis, o hidrogênio baixo teor de carbono possibilita praticamente zero emissões de gases de efeito estufa durante o consumo, consolidando-se como tecnologia estratégica para a diversificação da matriz energética brasileira e para o cumprimento de metas globais de mitigação climática.

Adicionalmente, ressalta-se a viabilidade da implementação dessa tecnologia, a depender de um planejamento adequado, que inclua infraestrutura de produção e abastecimento, capacitação de equipes, financiamento e políticas públicas de incentivo, bem como de parcerias entre os setores público e privado.

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ENERGY AND EXERGY ANALYSIS OF A THREE PASS FIRETUBE BOILER WITH TURBULATORS OPERATING WITH NATURAL GAS UNDER STEADY STATE CONDITIONS

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ABSTRACT

Industrial boilers are essential in modern production systems, providing the heat required for reactors, dryers, heat exchangers, and other unit operations. Their performance directly affects process efficiency, fuel consumption, and environmental impact. This study develops and validates a thermo-exergetic numerical model of a two-pass fire-tube boiler with a steam capacity of 150 kg/h, operating at 1–3 bar with non-submerged turn boxes and fueled by Bolivian natural gas. Configurations with and without internal turbulators were analyzed to assess their influence on energy efficiency, exergy efficiency, and irreversibility. A mesh test confirmed numerical stability beyond 350 control volumes, and model validation showed good agreement between simulated and measured flue-gas temperatures. A Central Composite Design (CCD) was applied to evaluate the combined effects of five parameters first-pass tube diameter, second-pass tube diameter, boiler length, number of tubes, and excess air ratio and to build a second-order polynomial model to maximize efficiencies and minimize irreversibility. The models exhibited high predictive accuracy (R^2>0.99). Boiler length and tube number were the most influential positive factors, while excess air had a negative impact. Adding turbulators increased energy efficiency (74.17 - 76.94 %), exergy efficiency (25.12 - 33.39 %), and reduced irreversibility (2.879×10^5 - 2.046×10^5 [W]). The optimized configuration achieved 83.91 % energy efficiency and 38.40 % exergy efficiency. The results confirm that combining turbulence-enhancing inserts with statistical optimization provides a practical, low-cost strategy to improve heat recovery and lower CO_2 emissions in small-capacity industrial boilers.

KEYWORDS
Thermodynamics, Combustion, Design of experiments, Tube bundles, Heat transfer.

1 INTRODUCTION

Steam generation is a fundamental component of industrial processes such as chemical reactors, heat exchangers, and dryers. In this context, boilers form the core of most heat-generation systems, particularly in the chemical, food, and paper industries. Natural-gas-fired boilers typically achieve efficiencies between 76 % and 81 %, but losses of up to 30 % may occur due to poor maintenance, excessive air-fuel ratios, or high flue-gas temperatures. Recent studies (2019-2025) have shown that the incorporation of internal turbulators in fire-tube boilers effectively enhances convective heat transfer and thermal efficiency, achieving flue-gas temperature reductions of up to 180 °C and efficiency increases between 3 % and 10 %, depending on the insert geometry [2] [5] [11]. Although this improvement entails higher pressure drops, the trade-off between enhanced heat transfer and acceptable hydraulic losses remains favorable for industrial applications. Nevertheless, few studies have simultaneously combined numerical simulation, exergy analysis, and experimental validation in real low-pressure boilers equipped with turbulators. Most focus solely on thermal efficiency without addressing irreversibility quantification or the combined optimization of geometric and operating parameters. Therefore, it is relevant to compare available literature data with the results of the present study (Table 1).

Table 1. Results of efficiencies in literature

Steam production capacity [t/hr]	Energy Efficiency [%]	Exergetic Efficiency [%]	Irreversibility Rate [%]	Configuration / Remarks	Reference
3	72.46	24.89	52	Conventional fire-tube boiler	Saidur et al. (2010)
637.8	85	41	Not identified	Industrial natural-gas boiler	Pattanayak & Ayyagari (2014)
Not identified	82	33	Not identified	Gas-fired fire-tube, simulation	Terhan & Comakli (2017)
Not identified	65	Not identified	Not identified	Industrial water-tube	Zeng et al. (1999)
10–11.6	83.79–85.29	13.41–27.97	Not identified	Biomass-fired boiler	Zhang et al. (2018)
1	Up to 90	Not analyzed	–	Experimental, twisted-tape inserts	Amori & Insayif (2011)
1.2	84–88	Not analyzed	–	Experimental, twisted + helical wire inserts	Neshumayev et al. (2004)
0.15	**74.17**	**25.12**	**2.879×10^5**	**Two-pass boiler without turbulators**	**This study**
0.15	**76.94**	**33.39**	**2.046×10^5**	**Two-pass boiler with turbulators**	**This study (with turbulators)**

Conventional fire-tube boilers typically achieve energy efficiencies between 70 % and 85 % and exergy efficiencies ranging from 13 % to 41 %, depending on fuel type and operating conditions. Studies involving turbulators show significant thermal improvements but lack exergy and irreversibility assessments. This work addresses that gap by integrating energy and exergy analyses, numerical modeling, and experimental validation in a real low-pressure fire-tube boiler equipped with locally manufactured turbulators. The model was applied to a two-pass boiler fueled by natural gas and installed at the Heat and Power Laboratory of the Department of Mechanical Engineering, Universidad Mayor de San Simón (UMSS), Cochabamba, Bolivia. It enables quantification of global irreversibility and evaluation of key geometric and operational parameters tube diameter and number, boiler length, and excess air through a Central Composite Design (CCD).

2 BOILER MODELING

A steady-state model is developed for the heat transfer of a two-pass firetube boiler, with non-submerged turning boxes. The steam generation process, considered as saturated steam, is isobaric. The boiler is modeled as a set of several heat exchangers in series, submerged in a uniform volume of saturated water. A two-phase water/steam zone, metal zone, and gas zone, respectively. The gas zones of the combustion chamber and tube bundle are subdivided into elementary sections; for each section, an energy balance is established considering the power generated and transferred in the control volume of length Δx in the direction of the gas flow, as shown in Fig. 1. The temperature, pressure, and composition of the gases are uniform in the control volumes. Additionally, both reactants and products are considered ideal gases.

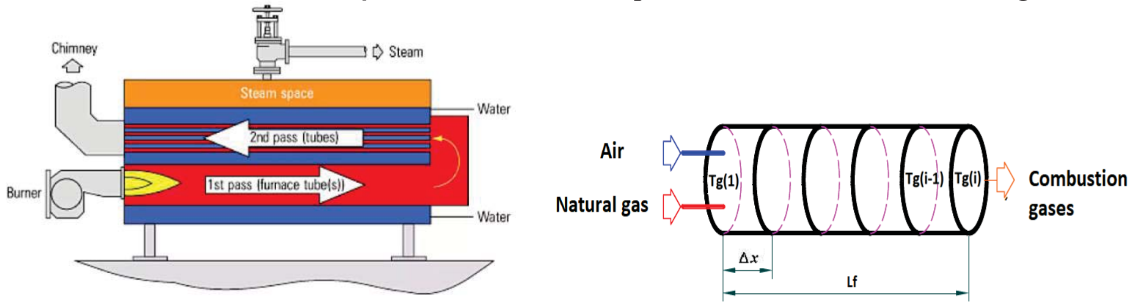

Fig. 1. Schematic representation of the two-pass firetube boiler (Spiraxsarco, 2021) and boiler subdivision scheme. (Self-elaboration)

2.1 Combustion modeling

The studied fuel is a Bolivian natural gas (92.10% of CH_4, 4.56% ofC_2H_6, 1.23% of C_3H_8, 0.15% of C_4H_{10}, 0.32 of C_4H_{10}, 0.10% of C_5H_{12}, 0.10% of C_5H_{12}, 0.22% of C_6H_{14}, 0.73% of N_2 and 0.48% of CO_2). The complete combustion process is considered, producing only carbon dioxide (CO_2) and water vapor (H_2O). A gradual combustion model along the length of the furnace is used. The length of the flame is assumed to be approximately equal to 70% of the length of the boiler [3]. The pattern of heat release along the flame (ie, the progress of the reaction and consequently the proportion of gas burned), F, can be described exponentially [15], parabolic [16] or uniformly. In the present work, the parabolic shape proposed by Roesler is applied [7] according to the equation Eq. (1)

$$F = \frac{6}{L_f} \cdot \left(\frac{x}{L_f} - \frac{x^2}{{L_f}^2} \right) \qquad \text{for} \quad 0 \leq x \leq L_f ; F = 0 \qquad \text{for} \quad x > L_f \tag{1}$$

where L_f is the flame length [m] and x:is the length within the first pass [m].

The chemical composition of the flue gases varies in each control volume as a function of the gradual combustion pattern.

2.2 Conservation equations

For each control volume, an energy balance is established considering the heat released by the combustion reaction (inside the flame) and the heat transferred to the water. For the control volume analysis of the second pass, a single tube is analyzed. Thus, the mass flow at the tube inlet is divided among the number of tubes in the second pass. The energy balance for a generic control volume is shown in Fig. 2.

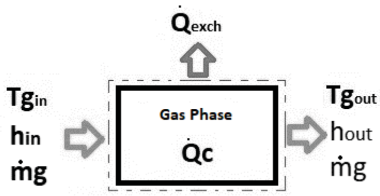

Fig. 2. Simplified scheme of transport phenomena in a control volume (Self-elaboration)

The steady-state energy conservation equation for a control volume is given by Eq. (2) which can be positive, null, or negative.

$$\dot{m}_g \cdot (h_{g:out} - h_{g:in}) = \dot{Q}_c - \dot{Q}_{exch} \Leftrightarrow T_{out} = \frac{\dot{Q}_c - \dot{Q}_{exch}}{\dot{m}_g \cdot cp_g} + T_{in} \tag{2}$$

where m_g is the mass flow of flue gas $\left[\frac{kg}{s}\right]$, $h_{g:out}$ is the output specific enthalpy $\left[\frac{J}{kg}\right]$, $h_{g:in}$ is the input specific enthalpy $\left[\frac{J}{kg}\right]$, $\dot{Q}_c$ is the combustion heat release rate $[W]$, $\dot{Q}_{exch}$ is the rate of heat transfer from flue gas to metal $[W]$, T_{out} is the flue gas outlet temperature $[K]$ and T_{in} is the flue gas inlet temperature $[K]$.

2.3 Equations for heat exchange

The radiative heat transfer coefficient was estimated using Talmor's correlation [20] for natural-gas flames, considering combined wall and gas emissivity's (ε_m=0.8, ε_gas from LHV) as suggested by [18].

The internal convective heat transfer coefficient hg was determined considering the temperature variation between the gas and the metal wall as described in [14] [8]. For turbulent flow in smooth tubes (Reint > 2300), the Nusselt number was calculated using the Gnielinski correlation [10]. For transitional conditions (2300 < Reint < 4000), a linear interpolation between laminar and turbulent regimes was adopted. The final expression is:

$$Nus_{Turb}(Gnielinski) = \frac{\frac{\xi_{nu}}{8} \cdot [Re_{int} - 1{,}000] \cdot Pr_g}{\left|1 + 12.7 \cdot \left[\frac{\xi_{nu}}{8}\right]^{1/2} \cdot [{Pr_g}^{2/3} - 1]\right|} \tag{3}$$

where ξ_{nu} is the friction factor, Pr_g the Prandtl number, and Reint the internal Reynolds number of the gas mixture [14] [8] [10].

For the external convective heat transfer coefficient h_o the literature presents the Gorenflo nucleate boiling correlation [4] for the combustion chamber given by Eq. (4).

$$h_o = 5{,}600 \cdot \left[1.73 \cdot Pr_2^{0{,}27} + \left[6.1 + \frac{0.68}{1 - Pr_2}\right] \cdot Pr_2^2\right] \cdot \left[\frac{\dot{Q}_{exch}}{S_{to} \cdot 20{,}000}\right]^{0.9 - 0.3 \cdot Pr_2^{0.t15}} \tag{4}$$

where Pr_2 is the reduced pressure $[-]$

Next to the tube bundle, the boiling heat transfer coefficient can be estimated using the correlation proposed by Fritz for tube bundles, expressed by Eq. (5):

$$h_o = 1.95 \cdot \left(\frac{\dot{Q}_{exch}}{S_{to}}\right)^{0.72} \cdot \left(\frac{P}{100{,}000}\right)^{0.24} \tag{5}$$

where P is the boiler working pressure $[Pa]$.

2.4 Turbulators

For the internal convective heat transfer coefficient in the tube bundle equipped with turbulators, h_{Turb}, according to the design and geometry of the turbulator used, the following correlations were identified in the literature. The correlation proposed by Petukhov (1970), Eq. (6), is used to calculate the convective heat transfer coefficient for smooth tubes fitted with turbulator inserts.

$$Nu = \frac{(f/8)\mathrm{Re_{int}} * \mathrm{Pr_g} * c_t}{1 + \frac{900}{\mathrm{Re_{int}}} + 4.5 f^{1/2}\left(\mathrm{Pr_g}^{2/3} - 1\right)} \tag{6}$$

In Eq. (6), the friction factor f is determined from Eq. (7).

$$f = (1.82\,\lg\,(\mathrm{Re_{int}}) - 1.64)^{-2} \tag{7}$$

Where the correction factor c_t is determined according to Žukauskas (1972), assuming that the turbulent boundary layer develops along the tube wall.

2.5 Exergetic analysis

Exergy is a property that allows determining the useful work potential of a given amount of energy in a given state in relation to its environment [9]. Total exergy derives from disordered forms of energy in an idealized device where the current would go through physical and chemical processes while interacting with the environment. It is convenient, however, to separate physical exergy from chemical exergy allowing the calculation of exergy values using standard chemical exergy tables [9]. Thus, the specific exergy rate ε $\left[\frac{J}{mol}\right]$ is:

$$\varepsilon = \varepsilon_k + \varepsilon_p + \varepsilon_{ph} + \varepsilon_0 \tag{8}$$

where ε_k is the specific kinetic exergy $\left[\frac{J}{mol}\right]$, ε_p is the specific potential exergy $\left[\frac{J}{mol}\right]$, ε_{ph} is the specific physical exergy $\left[\frac{J}{mol}\right]$ and ε_0 is the specific chemical exergy $\left[\frac{J}{mol}\right]$. In this work, kinetic and specific exergy potential components are considered negligible. For an ideal gas, the specific physical exergy ε_{ph} assuming the value of the specific heat at constant pressure invariant with temperature is given by the following Eq. (9).

$$\varepsilon_{ph} = \mathrm{cp_g} \cdot [\mathrm{T_g} - \mathrm{T_0}] - \mathrm{T_0} \cdot \left[\mathrm{cp_g} \cdot \ln\left(\frac{\mathrm{T_g}}{\mathrm{T_0}}\right) - \mathrm{R} \cdot \mathrm{Ln}\left(\frac{\mathrm{P_g}}{\mathrm{P_0}}\right)\right] \tag{9}$$

where P_g is the flue gas pressure $[kPa]$ and R is the universal gas constant considered equal to 8.314472 $\left[\frac{J}{mol.K}\right]$.

The studied substance consists of a mixture of gases, considered to be ideal, mixtures of natural gas, air and combustion products. The specific chemical exergy of the gas mixture is given by the following Eq. (10). [9].

$$\varepsilon_0 = \sum_i \mathrm{x_i} \cdot \tilde{\varepsilon}_i + \mathrm{R} \cdot \mathrm{T_0} \cdot \sum_i \mathrm{x_i} \cdot \mathrm{Ln}(\mathrm{x_i}) \tag{10}$$

where $\tilde{\varepsilon}_i$ is the molar exergy of each compound in the gas mixture $\left[\frac{J}{mol}\right]$ [9] and x_i is the molar fraction each compound of the reactants and combustion oxidant $[mol]$.

To calculate the standard molar chemical exergy of the gaseous fuel (ε_{fuel}), the expression proposed in [19] was used, considering the contributions of products and reactants as:

$$\varepsilon_{fuel} = -\Delta G + \sum \mathrm{n_p} \cdot \varepsilon_{Ch,P} - \sum \mathrm{n_R} \cdot \varepsilon_{Ch,R} \tag{11}$$

where ΔG is the change in the standard Gibbs function (≈ -1.778×10^6 J/mol), εch,p and εch,R are the molar chemical exergies of combustion products and reactants, respectively [9,19].

3 METODOLOGY

3.1 Boiler Description and Turbulator Design

The experimental setup consists of a two-pass fire-tube boiler installed at the Heat and Power Laboratory of Universidad Mayor de San Simón. The boiler operates with a steam production capacity of 150 [kg/h], a working pressure of 1.1 [Bar], a feedwater temperature of 20 °C, and is fueled with Bolivian natural gas at a flow rate of 0.004 [kg/s] and 19 % excess air. The furnace has an internal diameter of 0.24 [m], and the second pass comprises a bundle of 23 tubes with an internal diameter of 0.044 [m] and a length of 1.2 [m].

To enhance convective heat transfer, the tubes were equipped with internally fabricated turbulators (Fig. 3) made of 1.5 [mm] thick carbon steel sheets, each 0.240 [m] long, 0.044 [m] wide, and with a 0.160 [m] pitch. These inserts were designed to promote swirl flow, increase the internal heat transfer coefficient, and maintain mechanical stability during operation.

Fig. 3. Turbulator geometry and installation.

3.2 Validation

To validate the numerical model of heat transfer in the boiler, a mesh test was first performed, in which meshes with up to 350 regular control volumes (in the combustion chamber and in the second pass) were tested to analyze the temperature behavior and determine the length of each control volume. Once the appropriate mesh was determined, the temperatures obtained from the numerical model were compared with those measured experimentally, verifying that the values showed reasonable agreement.

3.3 Design of experiments

A Design of Experiments (DoE) consists of systematically varying input variables to identify their effect on the output response. Its main goals are to determine the most influential factors, define their optimal levels to approach the desired response, minimize variability, and reduce the impact of uncontrollable parameters [6]. In this work, a Central Composite Design (CCD), also known as Box–Wilson composite design [1], was applied, fitting the results to a second-order polynomial model through multiple regression analysis, as shown in Eq.(12).

$$Y = \beta_0 + \sum \beta_i X_i + \sum \beta_{ii} X_i^{2} + \sum \beta_{ij} X_i \cdot X_j \tag{12}$$

Where Y is expected response, β_0 is interception coefficient or constant term, β_i is coefficient of the linear effect of the variable i, β_{ii} is coefficient of the quadratic effect of the variable i and β_{ij} is coefficient of the interaction term (or rectangular) between variables i and j. For each variable, the influence of all factors and their linear relationships are studied. The investigated parameters and their respective levels are shown in Table 2.

Table 2. Variable geometric parameters and values of CCD factors (5 factors)

Symbol	Variable	Unit	-1	0	+1
X_1	D_{Fo} Tube diameter in step 1	[m]	0.14	0.24	0.34
X_2	D_{To} Tube diameter in pass 2	[m]	0.042	0.044	0.047
X_3	L_F Boiler length	[m]	0.95	1.20	1.45
X_4	N_{tub2} Number of tubes in pass 2	[-]	18	23	28
X_5	% Excess of air	[%]	9	19	29

4 RESULTS AND DISCUSSIONS

4.1 Parametric analysis in the objective of optimizing boiler efficiency

A mesh test was performed to define the adequate number of control volumes for the boiler model. The average gas temperature was monitored as the mesh was refined until results became stable. From 350 control volumes onward, temperature variations were negligible; this configuration was adopted to ensure sufficient resolution with reasonable computational cost. Model validation compared simulated and experimental gas temperatures at the outlet of each pass without turbulators, obtaining differences of 27 °C in the first pass and 72 °C in the second. These deviations stem mainly from unaccounted thermal losses in the turning box and external walls. Overall, the model reproduced the thermal behavior accurately, confirming that the selected discretization and correlations properly represent steady-state conditions.

4.2 Parametric analysis in the objective of optimizing boiler efficiency

Table 3. Regression coefficient, Student test and p-value for energy, exergetic efficiency and rate irreversibility (significant parameters are given in red)

Factor	Energy efficiency [%]			Exergetic Efficiency [%]			Rate of irreversibility [W]		
	Coefficient	Test-t	p-value	Coefficient	Test-t	p-value	Coefficient	Test-t	p-value
Mean/Intercept	7576076	6411213	0.000000	3254542	3832967	0.000000	1499317	1222098	0.247212
(1)X1 (L)	-0.39556	-40586	0.001888	-0.57222	-40856	0.001803	694	0.000686	0.999465
X1 (Q)	0.54618	20721	0.062549	0.77104	20355	0.066620	-2264405	-0.827453	0.425567
(2)X2 (L)	-0.45444	-46629	0.000690	-0.65333	-46647	0.000688	1128217	1115016	0.288611
X2 (Q)	0.50618	19203	0.081109	0.72104	19035	0.083457	7883095	2880620	0.014955
(3)X3 (L)	458278	470220	0.000000	647778	462506	0.000000	-3961	-0.003915	0.996947
X3 (Q)	-117886	-44722	0.000943	-161896	-42739	0.001312	-2263405	-0.827088	0.425676
(4)X4 (L)	282167	289520	0.000000	398556	284564	0.000000	-2556	-0.002526	0.998030
X4 (Q)	-0.76882	-29168	0.014019	-106966	-28220	0.016608	-2263755	-0.827125	0.425696
(5)X5 (L)	-251667	-258225	0.000000	-355111	-253545	0.000000	4267	0.004217	0.996711
X5 (Q)	-0.26382	-10009	0.333837	-0.35896	-0.9476	0.363667	-2264055	-0.827325	0.425637
1L by 2L	-0.05250	-0.5079	0.621571	-0.05750	-0.3871	0.706092	-250	-0.000233	0.999818
1L by 3L	-0.60500	-58526	0.000110	-0.86250	-58060	0.000110	862	0.000804	0.999373
1L by 4L	-0.61250	-59252	0.000099	-0.88000	-59238	0.000091	875	0.000815	0.999364
1L by 5L	-0.63000	-60945	0.000078	-0.90500	-60921	0.000077	875	0.000815	0.999364
2L by 3L	-0.51500	-49940	0.000314	-0.88000	-59238	0.000091	800	0.000727	0.999419
2L by 4L	-0.51500	-49820	0.000304	-0.74250	-49982	0.000404	900	0.000839	0.999346

Table 3. (continued)

Factor	Energy efficiency [%]			Exergetic Efficiency [%]			Rate of irreversibility [W]		
	Coefficient	Test-t	p-value	Coefficient	Test-t	p-value	Coefficient	Test-t	p-value
2L by 5L	-0.61750	-59736	0.000093	-0.88750	-59743	0.000093	900	0.000839	0.999346
3L by 4L	-0.46500	-44983	0.000933	-0.59250	-39894	0.001228	-388	-0.000362	0.999797
3L by 5L	0.17250	16687	0.123354	0.19750	13295	0.210602	-313	-0.000291	0.999773
4L by 5L	0.01000	0.0967	0.924675	-0.01500	-0.1010	0.921389	-200	-0.000186	0.999855

For the parametric analysis, a Central Composite Design (CCD) was applied to evaluate the influence of five parameters on the boiler's energy and exergy efficiencies and on the irreversibility rate. For the two-pass fire-tube boiler, with and without turbulators, the results ranged from 74.17 % to 76.96 % for energy efficiency, 25.12 % to 33.39 % for exergy efficiency, and 2.879×10^5 to 2.046×10^5 W for irreversibility. These values are consistent with those reported in the literature (Table 1), with differences mainly attributed to the smaller capacity and distinct geometry of the boiler analyzed. From the simulated efficiencies and irreversibility, the coefficients of the polynomial model were determined. Table 3 lists the regression coefficients together with their t-Student and p-values, highlighting in red those statistically significant at the 95 % confidence level ($p < 0.05$).

4.3 Analysis of energy, exergy and irreversibility performance

The Central Composite Design models show a high predictive capacity for both energy and exergy efficiencies ($R^2\approx0.997$), while the irreversibility rate exhibits a moderate fit ($R^2\approx0.49$), consistent with the natural variability of entropy generation and thermal fluctuations. In all cases, regression coefficients clearly identify the most influential geometric and operational parameters.

In the energy model, boiler length (X_3) and the number of tubes (X_4) present the highest positive linear effects (coefficients 4.58 and 2.82, $p<0.001$), confirming that increasing the heat exchange surface enhances overall efficiency by improving heat recovery from the flue gases. However, their negative quadratic terms (-1.17 and 0.76) indicate the existence of an optimum point, beyond which excessive length or tube number reduces gas velocity and heat transfer effectiveness. Excess air (X_5) exhibits a highly significant negative linear effect (-2.51, $p<0.001$), showing that oversupply of air lowers gas temperature and thermal efficiency. Significant interactions between X_1-X_3, X_1-X_4, and X_2-X_5 ($p<0.001$) indicate that optimal performance arises from a balance between geometry, flow distribution, and combustion conditions.

Exergy behavior follows a similar trend. Boiler length (X_3) and number of tubes (X_4) again have the strongest positive effects (3.23 and 1.99, $p<0.001$), while their quadratic terms (-0.80 and -0.53) define the point of maximum exergy efficiency. Excess air (X_5) shows a pronounced negative influence (-1.77, $p<0.001$), linked to higher exergy destruction by gas dilution and loss of useful potential. Tube diameters (X_1, X_2) also have negative linear and quadratic effects, indicating that larger flow areas decrease the Reynolds number and convective intensity.

For the irreversibility rate, the most influential factor is the second pass tube diameter (X_2), with a significant positive quadratic term (7.88×10^6, $p=0.015$). This confirms that larger flow areas weaken turbulence and increase entropy generation. Conversely, boiler length (X_3) and tube number (X_4) show negative effects, implying that greater exchange surfaces tend to reduce internal energy degradation. Interactions between geometric variables and excess air were not statistically significant ($p>0.4$), indicating that irreversibility is mainly governed by internal flow characteristics rather than combined effects.

Overall, the results confirm that the best thermo-exergetic performance is achieved through simultaneous optimization of boiler length, tube number, and a moderate level of excess air. The turbulators designed for this study enhance internal turbulence and flow uniformity, reduce entropy generation, and enable superior energy and exergy efficiencies under steady-state operation.

4.4 Optimization and Conclusions

The optimization based on the Central Composite Design identified the most influential variables governing the thermo-exergetic behavior of the two-pass fire-tube boiler equipped with turbulators. Five factors were analyzed simultaneously: first-pass tube diameter (X_1), second-pass diameter (X_2), boiler length (X_3), number of second-pass tubes (X_4), and excess air (X_5). Statistical analysis showed excellent predictive capacity ($R^2>0.99$ for energy and exergy efficiencies), highlighting X_3, X_4, and X_5 as dominant. The boiler length (X_3) and number of tubes (X_4) exhibited the strongest positive linear effects ($p<0.001$), confirming that extending the gas flow path and increasing the exchange surface enhance both energy and exergy efficiencies. Their negative quadratic terms revealed an optimum region where further geometric increase reduces gas velocity and convective effectiveness. Conversely, excess air (X_5) exerted a strong negative influence ($p<0.001$), as high air ratios lower flue-gas temperature and increase exergy destruction. The interactions X_2-X_5 and X_3-X_4 were also significant, evidencing the importance of geometry combustion coupling in determining overall boiler performance. For irreversibility, the model showed moderate correlation ($R^2 \approx 0.49$), consistent with the non-linear nature of entropy generation. The quadratic term of X_2 ($p=0.015$) was positive, indicating that larger flow areas reduce turbulence and increase entropy generation. On the other hand, X_3 and X_4 showed negative effects, demonstrating that greater exchange surfaces mitigate internal energy degradation. The CCD optimization identified an optimal configuration of $X_3=1.45$ [m], $X_1=0.14$ [m], $X_2=0.047$ [m], $X_4=28$, and $X_5=9$ %, resulting in 83.91 % energy efficiency, 38.40 % exergy efficiency, and a minimum irreversibility of 1.935×10^5 W. Compared to the configuration without turbulators, the installation increased energy efficiency (74.17 - 76.94 %), exergy efficiency (25.12 - 33.39 %), and reduced irreversibility (2.879×10^5 - 2.046×10^5 [W]). These improvements confirm that balancing gas velocity, exchange area, and air ratio is essential for maximizing thermo-exergetic performance.

Comparison with literature. Conventional fire-tube boilers typically show energy efficiencies between 70-85 % and exergy efficiencies up to ~41 % [17], [12], [21]. Experimental works with turbulators, such as Amori & Insayif (2011), reported up to ≈90 % thermal efficiency and flue-gas temperature reductions of ~180 °C, while Bisetto et al. (2015) observed 3-10 % efficiency gains and 110-120 [K] chimney temperature drops. Similarly, Neshumayev et al. (2004) found that hybrid geometries improved convective coefficients but increased pressure drops.

The slightly lower efficiencies observed in this study can be attributed to the smaller steam production capacity (0.15 [t/h]) of the tested boiler, compared to the medium and large-scale units (1-11 [t/h] or more) evaluated in those references. At lower loads, the relative heat losses through walls and stack become more significant, reducing the attainable global efficiency. Nevertheless, the relative improvement achieved with turbulators in this study (≈+10% in exergy efficiency) is comparable to that reported in higher capacity systems, confirming that the enhancement mechanism is scale independent and directly linked to improved internal convection. Therefore, this work not only aligns with previous thermal trends but extends them by (i) quantifying exergy and irreversibility, (ii) determining optimal geometries via CCD, and (iii) providing experimental validation in a real low-pressure boiler with locally fabricated turbulators. In summary, the CCD approach proved effective in locating the operating window that maximizes thermo-exergetic performance with minimal entropy generation. The fabricated turbulators demonstrated measurable gains in convective transfer and global efficiency, providing a practical and low-cost strategy for fuel savings and CO_2 reduction in industrial boilers.

Future work will focus on testing the optimized configuration under different load and fuel conditions, extending the CCD approach to dynamic operation. Further studies will also address long term stability, pressure drop evaluation, and the design of alternative turbulator geometries to enhance heat transfer with minimal hydraulic penalty.

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BLOCKCHAIN AND THE CARBON MARKET: A SURVEY ON EMERGING TECHNOLOGIES FOR ENVIRONMENTAL GOVERNANCE

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ABSTRACT

The convergence between digital technologies and environmental governance has created new opportunities to enhance transparency, efficiency, and reliability in carbon markets. Although a growing body of literature examines the role of blockchain in emission accounting, supply-chain traceability, and carbon market infrastructures, existing studies rarely address cryptocurrency-based carbon projects or the emerging ecosystem of tokenized environmental assets. As an introductory study, this survey fills this gap by mapping blockchain applications not only in traditional carbon market mechanisms but also in decentralized, crypto-native initiatives catalogued on platforms such as CoinGecko. The analysis identifies current technological trends, highlights challenges related to scalability, interoperability, and regulatory harmonization, and explores the integration of blockchain with artificial intelligence (AI) and the Internet of Things (IoT) for advanced environmental monitoring. In addition, the study evaluates how these developments contribute to the United Nations Sustainable Development Goals (SDGs). By integrating both institutional and market-driven Web3 initiatives, this work provides a broader, more contemporary overview of blockchain's potential for sustainable innovation and digital transformation in environmental governance.

KEYWORDS
Blockchain, Carbon Market, Sustainability, Emerging Technologies

1 INTRODUCTION

The growing urgency of climate change mitigation has placed carbon markets at the center of global strategies for reducing greenhouse gas (GHG) emissions. These markets serve as an essential mechanism for balancing economic development with environmental responsibility, facilitating the trading of carbon credits that correspond to verified reductions in emissions. In regulated Emissions Trading Schemes (ETS), a carbon credit typically corresponds to permission to emit one metric ton of CO_2-equivalent, rather than a proven removal or avoidance of emissions. In these systems, credits are allocated or auctioned to regulated entities, which may trade them depending on their compliance needs. Thus, while the *cap* limits overall emissions, individual credit transactions do not necessarily represent direct removal from the atmosphere. Voluntary carbon markets, however, commonly issue credits based on verified emission reductions or removals. This distinction is essential for understanding how blockchain solutions interact with different market structures, particularly as governments and corporations rely on these mechanisms to pursue sustainability goals and meet international commitments such as those established under the Kyoto Protocol and the Paris Agreement [1].

However, traditional carbon markets face persistent challenges related to data transparency, traceability, and trust in emission verification processes. These limitations hinder the scalability and reliability of carbon trading systems, creating barriers to wider adoption and public confidence. In this context, blockchain technology—with its decentralized, tamper-proof, and auditable architecture—has emerged as a promising tool for environmental governance. It provides mechanisms for secure transaction recording, real-time data validation, and automation through smart contracts, which together can strengthen accountability in carbon credit management [2].

In recent years, blockchain has evolved beyond its origins in cryptocurrency to become a cornerstone of *environmental computing*. Its integration with other digital technologies, such as artificial intelligence (AI) and the Internet of Things (IoT), has opened new pathways for monitoring emissions, validating offsets, and supporting sustainable policies through data-driven decision-making. This technological convergence aligns with multiple United Nations Sustainable Development Goals (SDGs), especially SDG 7 (Affordable and Clean Energy), SDG 13 (Climate Action), and SDG 15 (Life on Land).

This paper provides a survey of blockchain-based applications, platforms, and initiatives focused on carbon markets and sustainability. It aims to map current technological trends, identify existing challenges, and outline future research opportunities in the emerging intersection between blockchain and environmental governance. The remainder of this paper is structured as follows: Section 2 introduces the theoretical background of blockchain; Section 3 explores its role in sustainability and alignment with the SDGs; Section 4 discusses major challenges and limitations; Section 5 presents some related works; Section 6 presents notable blockchain-based carbon projects; and Section 7 summarizes key findings and future directions.

2 THEORETICAL BACKGROUNDS

Blockchain technology originally emerged as the foundation for the Bitcoin cryptocurrency, described by Nakamoto in 2008 [2]. Since then, its use has expanded into several areas, including finance, supply chains, public administration, and, more recently, environmental sustainability. It is a distributed data structure that operates through a decentralized network of computers, in which each transaction is verified by a consensus mechanism, recorded in data blocks, and chronologically linked to previous blocks. This architecture ensures the immutability, integrity, and auditability of the stored information [4].

The blocks that compose the chain contain sets of validated and cryptographically protected transactions [8]. Each block is linked to the previous one via a unique identifier, known as a hash, which ensures the chain's continuity and integrity. Figure 1 illustrates the structure of a blockchain, where each block contains validated, cryptographically protected transactions, linked to the previous block via a unique hash to ensure continuity and integrity.

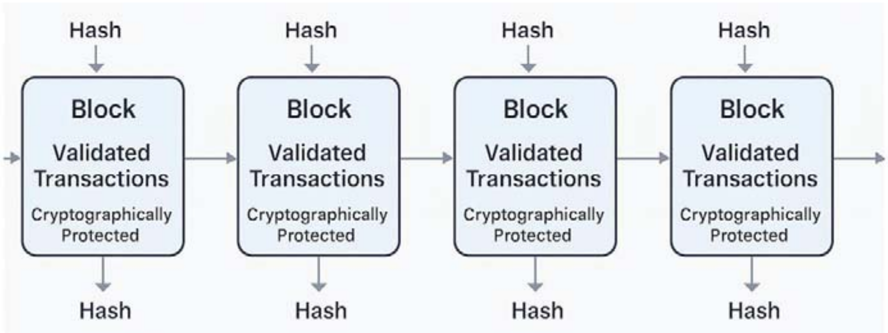

Figure 1: Representation of a blockchain structure, a sequence of blocks containing validated and cryptographically protected transactions, linked by unique hashes to ensure continuity and integrity.

Transaction validation and the generation of new blocks are carried out through consensus mechanisms, such as Proof of Work (PoW), which requires significant computational power, or Proof of Stake (PoS), which is more energy efficient [9]. Furthermore, the use of smart contracts—self-executing programs that run on the blockchain—enables automated processes and rule enforcement without intermediaries, thereby expanding the technology's applicability in complex contexts [10].

In the environmental field, blockchain has been applied notably to track sustainable supply chains, certify ecological practices, manage water resources, and monitor GHG emissions and manage carbon credits [11, 12]. By digitally and permanently recording the origin, transfer, and retirement of credits, blockchain helps increase trust in transactions and reduce uncertainties associated with conventional verification. When combined with other emerging technologies, such as IoT sensors and artificial intelligence, blockchain provides a solid foundation for developing intelligent environmental systems. These systems can support public policies, environmental audits, and carbon offset initiatives with greater efficiency, security, and transparency.

3 BLOCKCHAIN AND SUSTAINABILITY

Blockchain, known for its decentralized, immutable architecture, provides a transparent and secure platform for a wide range of applications. In the environmental domain, this technology has been applied to enhance the efficiency and reliability of carbon markets [13,14,15].

A Monitoring and Recording Emissions

The ability of blockchain to provide immutable records is crucial for accurately monitoring greenhouse gas emissions. By registering each ton of CO_2 emitted or reduced in a blockchain, data integrity is ensured, and double-counting of carbon credits is avoided. This is particularly important to maintain the credibility of carbon markets and ensure that each credit represents a genuine reduction in emissions [3].

B Trading and Certification of Carbon Credits

Blockchain-based smart contracts enable the automation of verification, validation, and trading of carbon credits. This reduces intermediaries, increases efficiency, and improves transaction transparency. In addition, decentralized platforms ensure that credits are exchanged reliably and without manipulation [7].

C Blockchain and the Sustainable Development Goals (SDGs)

The United Nations Sustainable Development Goals (SDGs) establish a global framework for fostering sustainable development and combating climate change [16]. Blockchain contributes to the SDGs by strengthening transparency, trust, and traceability across environmental and socio-economic processes [17]. Table 1 summarizes these contributions and distinguishes between direct and indirect impacts.

Table 1. Blockchain contributions to selected UN Sustainable Development Goals (SDGs).

SDG	Type of Contribution	How Blockchain Contributes	Examples of Applications
SDG 7 – Affordable and Clean Energy	Direct	Verifiable tracking and certification of renewable energy generation; peer-to-peer energy markets	Renewable Energy Certificates (RECs), decentralized solar trading
SDG 13 – Climate Action	Direct	Transparent emission accounting; prevention of double counting in carbon markets; automated credit retirement	Carbon credit registries; blockchain-based MRV systems
SDG 15 – Life on Land	Direct	Traceability of reforestation, conservation, and land restoration initiatives	Tokenized reforestation projects; immutable land-use records
SDG 8 – Decent Work and Economic Growth	Indirect	Creation of green digital markets; new economic opportunities via tokenization	Carbon-backed tokens; sustainable finance ecosystems
SDG 9 – Industry, Innovation and Infrastructure	Indirect	Development of resilient digital infrastructure; integration with IoT and AI for environmental monitoring	Smart contracts for sustainability; IoT–blockchain integration
SDG 16 – Peace, Justice and Strong Institutions	Indirect	Transparent governance mechanisms; immutable public records; reduction of information asymmetry	Public registries; digital auditability; secure environmental reporting

In summarising Table 1, it becomes evident that blockchain is not merely a technical novelty but a pivotal component of broader digital governance ecosystems aiming to accelerate sustainable development. By embedding traceability, auditability, and automation within environmental markets, blockchain can strengthen the credibility of instruments such as carbon registries, renewable-energy certificates, and land-use restoration schemes — thereby advancing direct targets such as SDG 7, SDG 13, and SDG 15. Simultaneously, its systemic features generate ripple effects across economic, infrastructural, and institutional domains, contributing indirectly to SDG 8, SDG 9, and SDG 16. Yet, the transition from potential to impact depends critically on the alignment of technology with regulation, stakeholder engagement, and cross-sectoral governance frameworks. As such, the deployment of blockchain-enabled sustainability solutions must be complemented by rigorous impact assessment, inclusive design, and energy-efficient infrastructure if the promise of truly sustainable digital markets is to be realised.

4 CHALLENGES OF BLOCKCHAIN IMPLEMENTATION

Although the use of blockchain in the carbon market brings significant advantages, its implementation faces several challenges [5]:

A Interoperability Between Blockchains

One of the main challenges for the sector is the lack of interoperability among different blockchain platforms. Currently, multiple blockchains operate in isolation, hindering the integration and transfer of carbon credits across distinct systems. To address this issue, it is essential to develop interoperability standards and compatible protocols that enable efficient and reliable transactions across networks.

B Scalability and Transaction Costs

The increased use of blockchain in the carbon market can pose scalability and transaction-cost challenges. Many public blockchains experience network congestion, resulting in longer processing times and higher transaction fees. Solutions such as second-layer (Layer 2) networks and high-performance blockchains can mitigate these issues, making the system more efficient and accessible.

C Regulation and Compliance

The absence of standardized regulation for blockchain use in the carbon market creates uncertainty for companies and investors. Governments and regulatory agencies must establish clear guidelines to ensure the validity and security of carbon credits traded on blockchain platforms. Moreover, adopting internationally recognized certifications can strengthen the system's reliability.

D Artificial Intelligence Challenges

The application of artificial intelligence (AI) to monitor and verify carbon credits also presents challenges. The accuracy of AI models depends on the quality of the data collected, and a lack of standardization may compromise system efficiency. Furthermore, ensuring the transparency of algorithms used to calculate carbon emissions is crucial to prevent fraud and market distortions.

E Non-technological Barriers to Adoption

Beyond technical limitations, transnational carbon markets face institutional, political, and economic barriers [18]. These include heterogeneous regulatory frameworks, differences in national accounting rules for emissions, a lack of mutual recognition of carbon standards, and concerns regarding market manipulation or greenwashing. Blockchain may enhance transparency and traceability, but it cannot by itself harmonize policies or ensure cross-jurisdictional acceptance of carbon credits. Therefore, any interoperable global carbon market requires coordinated governance frameworks that complement technological solutions.

5 RELATED WORKS

Recent studies have advanced the understanding of how blockchain can support environmental governance and carbon market mechanisms, with two publications standing out as the most up-to-date and comprehensive literature reviews on the topic. The first, Thanasi-Boçe & Hoxha [17], provides a broad systematic review of blockchain applications for sustainable development, emphasizing contributions to renewable energy certification, climate mitigation, and supply-chain transparency. Although it highlights the potential of decentralized systems for improving traceability and data integrity, the review remains centered on institutional frameworks, policy challenges, and theoretical applications, without examining market-driven blockchain projects operating within tokenized or cryptocurrency-based ecosystems.

Similarly, the second review, Merlo et al. [19], offers an in-depth analysis of blockchain's role in the carbon market, identifying benefits such as transparency, automation via smart contracts, and strengthened Monitoring, Reporting, and Verification (MRV) systems. The study also discusses major barriers, including interoperability, regulatory fragmentation, and the energy footprint of blockchain infrastructures. However, like the [17], it does not include or classify blockchain-native carbon initiatives that function through tokenized assets, decentralized finance (DeFi), or crypto-based carbon markets — many of which are actively tracked on platforms such as CoinGecko[1].

By incorporating these cryptocurrency-linked carbon projects into the analysis, the present work fills an important gap in the literature. While prior reviews focus primarily on conceptual, regulatory, or institutional perspectives, our survey integrates the academic landscape and the emerging ecosystem of tokenized environmental assets, offering a more contemporary, market-oriented view of how blockchain technologies are reshaping environmental governance.

6 CRYPTOCURRENCY PROJECTS IN THE CARBON MARKET

In recent years, the integration of blockchain, cryptocurrencies, and environmental sustainability has led to the development of a new class of applications centered on the carbon market. Cryptocurrency projects backed by carbon credits have gained prominence as

[1] http://www.coingecko.com

alternatives to increase liquidity, accessibility, and traceability in this market. These initiatives propose tokenizing environmental assets, such as verified carbon credits, and making them available on decentralized digital platforms, enabling global-scale trading with lower operational costs and greater transparency.

The data on the projects presented below were obtained from the CoinGecko platform. CoinGecko is widely used to aggregate and monitor crypto-asset market data, providing updated information on prices, trading volume, market capitalization, percentage variation, and data related to decentralized finance (DeFi), non-fungible tokens (NFTs), and exchanges. The platform is noted for its methodological transparency and for its public API, which facilitates data access for research and application development. Due to its scope and reliability, CoinGecko has become a primary reference in the cryptocurrency ecosystem and is widely consulted by researchers, developers, investors, and market analysts.

To identify cryptocurrency projects associated with environmental sustainability and the carbon market, a structured search was conducted on CoinGecko in May 2025 using keywords such as "carbon", "carbon credit", "carbon offset", "climate", "green", "sustainability", and "environment". This search produced an initial set of assets classified as "environmental", "tokenized credits", or "green initiatives". Each candidate project was then examined individually through the platform's descriptive pages, complemented by the analysis of official documentation, whitepapers, and project websites. It is important to note that, given the rapid growth of the blockchain and crypto-asset sector in recent years, new carbon-related tokens may have emerged after the data collection period. Consequently, the list presented in this study represents a current snapshot of the ecosystem as of May 2025, rather than an exhaustive or static catalog of all existing initiatives.

- One of the most notable examples of cryptocurrency projects is the Toucan Protocol. Operating on the Polygon blockchain, it enables the tokenization of carbon credits originated from international standards such as the Verified Carbon Standard (VCS). These credits are converted into digital tokens, such as BCT (Base Carbon Tonne), which can be traded through smart contracts and used in decentralized finance (DeFi). Toucan provides a bridge between the traditional market and the blockchain ecosystem, ensuring traceability, public auditing, and automated retirement of credits.
- The Carbon Emission Blockchain is a project that uses blockchain technology to record and validate carbon emissions in real time. Companies can acquire tokens representing certified carbon reductions, thereby increasing the transparency and reliability of environmental data.
- The Carbon platform aims to facilitate carbon credit trading and incentivize sustainable practices through a blockchain-based system. Its model ensures that each transaction is auditable and traceable, fostering confidence in the market.
- The Switcheo project integrates decentralized solutions for trading digital assets, including tokens backed by carbon credits. This approach improves liquidity and accessibility of carbon markets for investors and companies seeking emission offsets.
- Founded in 2021, KlimaDAO is a decentralized autonomous organization that uses BCT tokens as the basis for its cryptocurrency, KLIMA. Its goal is to incentivize carbon removal from the atmosphere by increasing demand for tokenized credits, thereby creating an economic ecosystem in which asset value is tied to sustainability.

Mechanisms such as staking and decentralized governance are employed to promote incentives and collective decision-making regarding protocol management.

- Launched in March 2020, Moss Carbon Credit (MCO2) is one of the world's largest environmental platforms, using blockchain technology to preserve the environment. MCO2 is backed by carbon credits, which are used to offset CO2 footprints. Through tokenization, the asset is directed towards projects focused on environmental preservation.
- Universal Carbon (UPCO2) is the world's first interchangeable carbon token on a public blockchain. Each token represents one ton of CO2 that has been avoided through certified emission reduction projects, enabling individuals and companies to offset their emissions in a transparent and traceable manner.

Table 2 provides a comparative overview of the main blockchain-based cryptocurrency projects in the carbon market, highlighting their platforms, token types, and application areas.

Table 2: Comparative overview of blockchain-based cryptocurrency projects in the carbon market. Source: https://www.coingecko.com/

Project	Blockchain	Token Type	Main Focus
Toucan Protocol	Polygon	BCT (Base Carbon Tonne)	Tokenization of carbon credits (VCS), DeFi integration
Carbon Emission Blockchain	Not specified (proprietary)	Carbon reduction tokens	Real-time recording and validation of carbon emissions
Carbon Platform	Proprietary blockchain	Carbon credits	Auditable and traceable carbon credit transactions
Switcheo	Multi-chain (incl. Ethereum)	Carbon-backed tokens	Decentralized exchange, liquidity for carbon assets
KlimaDAO	Polygon	KLIMA (backed by BCT)	Incentivizing carbon removal via demand for tokenized credits
Moss Carbon Credit (MCO2)	Ethereum	MCO2 Token	Preservation projects, CO2 footprint offsetting
Universal Carbon (UPCO2)	Ethereum (public blockchain)	UPCO2 Token	Interchangeable carbon token, 1 ton CO2 avoided per token

In addition to these, there are ongoing initiatives in Brazil, such as startups exploring blockchain for supply chain traceability, real-time emissions measurement, and the issuance of green tokens linked to projects for forest preservation or regenerative agriculture. Such initiatives aim to align the requirements of regulated markets with the technological capabilities of crypto-assets and smart contracts.

Although promising, these projects face challenges related to standardization, interoperability between blockchains, validation of tokenized credits, and regulatory compliance, particularly in countries that have not yet established clear legal frameworks for environmental digital assets. Nevertheless, the growing convergence between cryptocurrencies and carbon credits points to a new paradigm of environmental governance, in which blockchain technology plays a central role in the digital transformation of sustainability.

7 FINAL CONSIDERATIONS

This survey examined how blockchain and related emerging technologies contribute to modernizing carbon markets and environmental governance. The analysis demonstrates that blockchain presents significant potential to enhance transparency, traceability, and efficiency in carbon credit systems, particularly when combined with artificial intelligence and IoT architectures. This convergence establishes a promising frontier for environmental computing by enabling more reliable Monitoring, Reporting, and Verification (MRV) processes and supporting data-driven climate strategies.

Despite these opportunities, substantial challenges remain. Barriers to scalability, regulatory alignment, and interoperability persist, underscoring the need for coherent, coordinated global governance frameworks. Furthermore, most blockchain-based carbon initiatives remain experimental or operate exclusively within voluntary markets, with limited integration into regulated Emissions Trading Schemes (ETS). This scenario underscores the scarcity of empirical evaluations—especially those assessing environmental integrity, additionality, and permanence of tokenized credits—revealing a persistent gap in the literature. These limitations reinforce the view that blockchain should be understood as an enabling technology rather than a standalone solution to structural governance constraints.

Future research should therefore prioritize empirical assessments of blockchain adoption in carbon offset projects, including case studies in emerging economies such as Brazil. It should also investigate integrating blockchain with artificial intelligence, remote sensing, and real-time environmental monitoring tools to strengthen MRV capabilities. In addition, evaluating the energy performance and carbon footprint of blockchain infrastructures remains crucial, given the sustainability implications of different consensus mechanisms. Advancing cross-chain interoperability standards, assessing credit permanence, and aligning blockchain-based registries with Article 6.2 of the Paris Agreement constitute essential next steps for both researchers and policymakers. The official recognition and regulatory acceptance of tokenized carbon credits in national and international markets must also be addressed to unlock blockchain's full potential.

Ultimately, by bridging environmental computing and distributed ledger technologies, blockchain offers valuable infrastructure for developing transparent, reliable, and verifiable climate governance systems. When embedded within coherent regulatory frameworks and supported by rigorous impact assessment, blockchain can contribute meaningfully to the creation of sustainable digital ecosystems aligned with the United Nations Sustainable Development Goals and global climate action efforts.

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DESENVOLVIMENTO DE UMA BANCADA PARA SOLDAGEM EM OPERAÇÃO COM SIMULAÇÃO DE FUNDO DE TANQUE

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A indústria petroquímica frequentemente utiliza tanques para armazenagem de hidrocarbonetos. No contexto offshore, navios-tanque e FPSOs são empregados como unidades flutuantes de armazenamento. Os tanques de armazenamento são fabricados majoritariamente em aços de alta resistência e baixa liga (ARBL), sendo comumente adotado o aço ASTM A131 AH36 devido ao seu custo-benefício, resistência mecânica e boa soldabilidade. No entanto, em ambiente marinho agressivo, com presença de íons cloreto, compostos ácidos e CO2, os fundos de tanques ficam suscetíveis à corrosão localizada, resultando em perdas de espessura que podem levar a falhas catastróficas e vazamentos no oceano, causando danos graves ao meio ambiente. O reparo por soldagem em áreas corroídas, com espessuras remanescentes reduzidas, apresenta desafios críticos: risco de perfurar a chapa durante a soldagem e possibilidade de formação de trincas a frio induzidas por hidrogênio. Dessa forma, é necessário investigar técnicas de reparo e recomposição de espessura no fundo de tanque com segurança e confiabilidade. Para viabilizar esse estudo, foi desenvolvida uma bancada de soldagem em operação que representa o fundo de tanque, incluindo troca térmica simulada durante o reparo. O objetivo é oferecer um aparato experimental que permita investigar métodos adequados para recompor a espessura original e garantir a integridade estrutural durante o reparo. Desse modo foram realizadas soldagens de reparo com espessuras remanescentes de 4, 3 e 2 mm, com monitoramento da temperatura da água e das variáveis de soldagem através da instrumentação da bancada, demonstrando a efetividade da bancada.

Palavras-chave: Soldagem, Fundo de Tanque, Trincas a Frio Induzidas por Hidrogênio.

POTENTIAL OF CANAL STRAW (*SACCHARUM SPONTANEUM*) AND SUGARCANE BAGASSE (*SACCHARUM OFFICINARUM*) AS ENERGY BIOMASS IN PANAMA

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ABSTRACT

Canal straw (*Saccharum spontaneum*), an invasive species, and sugarcane bagasse (*Saccharum officinarum*), an agro-industrial waste product, represent underutilized resources with significant potential for energy biomass production in Panama. This study evaluates their availability and energy yield, showing that cogeneration with bagasse covers a significant part of the energy needs of sugar mills, while canal straw could be integrated into the energy mix through combustion, gasification, or biofuel production. Inadequate management of this waste, such as burning or accumulation, generates considerable environmental and health impacts, including carbon dioxide emissions and risks such as bagasse disease. In contrast, its sustainable use reduces emissions, improves soil quality through the use of ash as fertilizer, and promotes a circular economy. Analysis of its chemical properties reveals a cellulose content that favors biochemical processes, such as bioethanol production, and a lignocellulosic composition suitable for thermochemical applications. However, logistical challenges, such as the low energy density of sugarcane straw and the difficulties of storing bagasse, hinder its full exploitation. The study proposes strategies such as mechanized harvesting, tax incentives, and specific regulations to optimize its use. Inspired by models such as Brazil's, where bagasse contributes significantly to national electricity, Panama could position itself as a regional leader in bioenergy, generating employment and energy security. Future research is recommended to expand national inventories, optimize conversion processes, and evaluate the economic viability of these alternatives.

KEYWORDS
Biomass, canal straw, sugarcane bagasse, renewable energy, waste management, Panama.

INTRODUCTION

The global energy transition is driving the search for renewable sources to reduce greenhouse gas emissions and meet the objectives of the 2015 Paris Agreement, which seeks to limit global warming to 1.5°C [1]. Lignocellulosic biomass represents a key alternative, contributing 10% of the world's primary energy, equivalent to 1.2 billion tons of oil equivalent per year [2]. Agro-industrial residues, such as those derived from sugarcane, offer significant potential for generating renewable energy and reducing dependence on fossil fuels. In Panama, 70% of the energy mix depends on renewable sources, mainly hydroelectric, which accounts for 60% of installed capacity [3]. However, climate vulnerability, such as seasonal droughts, underscores the need to diversify energy sources. Sugarcane, with 50 000 ha under cultivation and an annual production of 2.5 million tons, is a strategic crop in the country [4].

Canal straw (*Saccharum spontaneum*), an invasive grass introduced into Panama in the first half of the 20th century [5], covers extensive areas of land throughout the country (approximately 7 000 ha in the Panama Canal basin) [6]. Due to its rapid germination, spread, and growth, it prevents the natural development of native flora [7]. This species survives in harsh environments and germinates in poor soils. During the dry season, it is the main target of deliberate or spontaneous burning, affecting humans and the environment. However, it is resistant and regrows quickly [8].

Its fast growth, reaching 3-4 m in height, generates up to 24 t of dry biomass per hectare per year [9]. This species, considered a pest, competes with native vegetation and increases the risk of forest fires, releasing between 1.5 and 2 t of CO_2 per ton of biomass burned [10]. However, its high lignocellulosic content allows it to be used in direct combustion, gasification, and the production of second-generation biofuels, such as cellulosic ethanol, with an estimated yield of 200 l/dry t [11].

¡Error! No se encuentra el origen de la referencia. shows the influence of canal straw in the Panama Canal watershed.

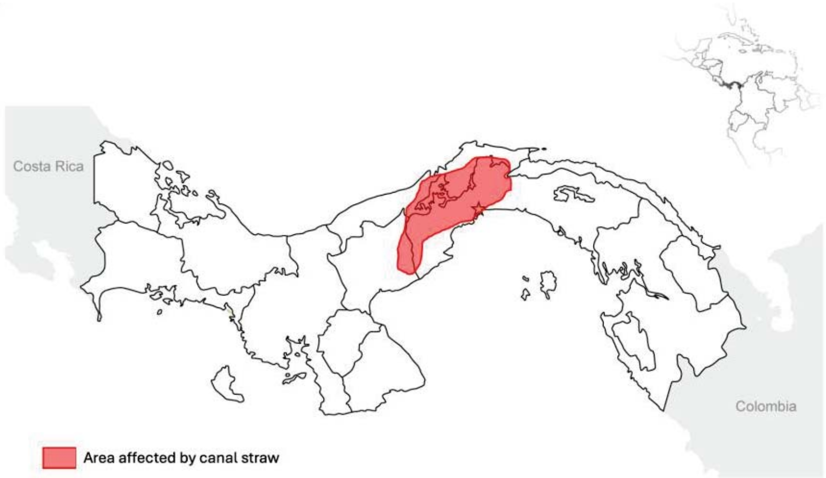

Fig. 1. Area affected by canal straw in the Panama Canal watershed.

Sugarcane bagasse (*Saccharum officinarum*), a fibrous residue left over after juice extraction, is produced in large quantities in Panamanian sugar mills. Sugarcane mills are facilities dedicated to the production of sugar, alcohol, and molasses. They are located in the central and western parts of the country. There are five mills in total, three private and two state-owned. The private mills are:

- Ingenio Ofelina S.A., in the district of Nata, province of Coclé, which is dedicated to the production of crystalline sugar, alcohol, and molasses. It generates 7.9 million kWh/day from bagasse, which is equivalent to 72% of the energy used in the process.
- Ingenio Santa Rosa S.A., located in El Roble, Aguadulce district, Coclé province, produces a total of 128 410 t of bagasse and generates 5.01 million kWh/day using bagasse, which is equivalent to 75% of the energy used in the process.

- Varela Hermanos S.A., located in the district of Pese, province of Herrera, produces 625 t/day of bagasse with 48% moisture content, which is used to produce steam during the milling and distillation processes.

The state-owned sugar mills are:

- Ingenio La Victoria in the township of La Raya, Santiago district, Veraguas province. This mill produces 219 035 t of bagasse and generates 866 100 kWh/day, equivalent to 90% of the energy used in the process.
- The other mill is located in the district of Alange, Chiriquí province, and has similar characteristics to the previous one.

More specifically, La Victoria sugar mill in Veraguas produces more than 219 000 wet tons of bagasse per harvest [12], with a chemical composition of 43% cellulose, 27% hemicellulose, and 18% lignin. This bagasse is ideal for cogeneration in high-pressure boilers, achieving 90% energy efficiency in modern mills [13]. At La Victoria, bagasse generates 866 100 kWh per day, covering most of the mill's energy needs [12]. The surplus, which represents 20-25% of the bagasse produced, offers opportunities for producing paper pulp, biochar, and organic fertilizers [14].

¡Error! No se encuentra el origen de la referencia. shows the location of sugar factories in Panama.

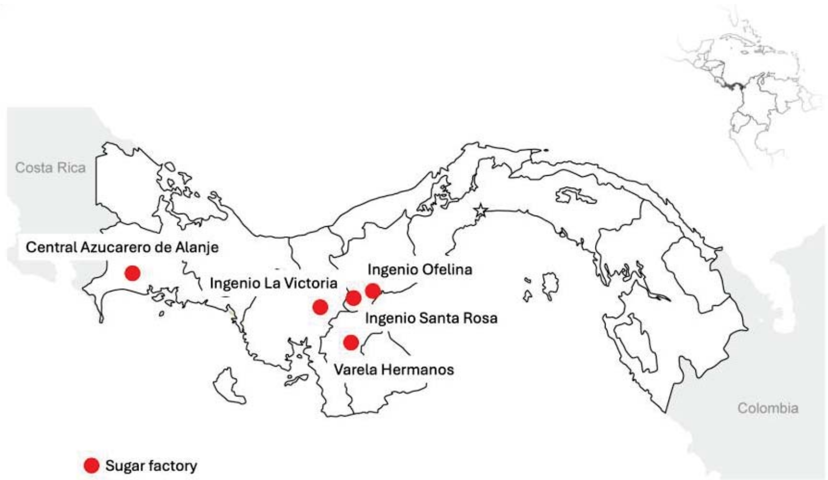

Fig. 2. Location of sugar factories in Panama.

Inadequate management of this waste has a significant environmental impact. The burning of canal straw causes loss of organic matter and air pollution, while the accumulation of bagasse produces leachates with a chemical oxygen demand of 1200 mg/L and fungal spores of 240-500 million per gram, associated with health risks such as bagassosis [14]. In contrast, the sustainable use of this waste in cogeneration reduces CO_2 emissions by up to 7 million tons per year globally [2] and improves soil quality through the use of ash as fertilizer. In Latin America, countries such as Brazil use bagasse to generate 7% of their national electricity [15], a model that can be replicated in Panama, where the infrastructure for collecting sugarcane bagasse faces logistical challenges due to its low energy density of 0.15 t/m³ [9].

This study evaluates the availability of sugarcane bagasse and straw in Panama, quantifying their energy potential through combustion, cogeneration, and biofuels, and analyzing the environmental impacts of their traditional disposal versus their sustainable use. Finally, the research proposes strategies to optimize the use of these resources, contributing to the diversification of the energy matrix, the reduction of emissions, and the development of a circular economy in the Panamanian context.

MATERIALS AND METHODS

Biomass harvesting and quantification

The harvesting of canal straw was carried out in the Panama Canal basin, specifically on 10 one-hectare plots located between the provinces of Panama and Panama Oeste in the Central American country, within the influence of the canal, selected by stratified random sampling to ensure representativeness [13]. Each plot was harvested manually during the month of May 2025.

Bagasse samples were obtained from the La Victoria (Veraguas) and Santa Rosa (Coclé) sugar mills during the January to April 2025 harvest, collecting several kilograms per batch in five replicates, following sampling protocols established by [12].

To estimate national bagasse production, the available information from the five main mills in Coclé, Veraguas, and Chiriquí was extrapolated based on regional yields [12].

The quantification of available biomass was carried out by gravimetric analysis. For sugarcane straw, three 1-kg samples per field plot were weighed using a Sartorius analytical balance with an accuracy of 0.01 g. The samples were dried in a Memmert UNE400 oven at 105°C for 48 hours to determine the dry biomass content.

For bagasse, three batches of 5 kg each were analyzed, determining the moisture content by drying at 70°C for 72 hours in the same oven, according to the method described by López et al. [14].

The energy potential was evaluated using calorimetry and direct production measurements. The calorific value of sugarcane bagasse was determined in a Parr 1341 pump calorimeter, following the standard [16], analyzing three samples of 1 g each. The total energy of the canal straw in the Canal basin (7000 ha) was calculated by multiplying the dry biomass yield by the calorific value. The same calorimetric method was used for bagasse.

Biomass characterization

The chemical characterization of the biomass was performed to evaluate its viability in energy and non-energy applications. Canal straw and sugarcane bagasse were analyzed to determine the cellulose, hemicellulose, and lignin content using the TAPPI T203 method [17]. Proximate analysis (volatile matter and ash) was performed following the guidelines of ASTM D3175 [18] and D3175 [19], respectively (fixed carbon is calculated by difference to 100). Ultimate analysis (carbon, hydrogen, nitrogen) was performed on a Thermo Scientific Flash 2000 elemental analyzer, following the ASTM D5373 [20] standard.

RESULTS

Biomass quantification

Quantification of available biomass revealed that sugarcane straw in the Panama Canal basin generates 168 000 tons of dry biomass per year, calculated from an average yield of 24 ± 2.3

tons per ha over 7 000 ha. This value is consistent with studies of invasive grasses in tropical regions, such as *Imperata cylindrica*, which report yields of 20-25 t/ha/year in Indonesia [21]. Regarding sugarcane bagasse, Table 1 shows production per harvest season for sugar mills.

Table 1. Production per harvest of sugar bagasse

Sugar factory	Production (t)	Moisture (% wb)	Calculated dry biomass (t)
La Victoria	219 035	49.8 ± 1.2	109 956
Santa Rosa	128 410	50.1± 3.1	64 077
Ofelina	202 482	48.2± 1.7	104 886
Alanje	200 000	Nd	100 000
Varela	30 250	Nd	15 125

* Nd: no data. It is estimated at 50.

According to these data, the national estimate for bagasse exceeded 780 000 wet tons per year (390 000 dry tons), which is slightly higher than regional estimates of 450 000-600 000 tons per year in Central American countries such as Guatemala [22]. The consistency of the bagasse moisture data coincides with reports from Brazil, where an average of 50 ± 2% is recorded [23].

The energy potential analysis showed that sugarcane bagasse has a heating value of 18.5 ± 0.4 MJ/kg dry weight, determined by calorimetry. This value is comparable to the heating value of *Panicum virgatum* (switchgrass), reported as 18.0-19.0 MJ/kg in studies in the United States [24].

For sugarcane bagasse, samples from La Victoria sugar factory recorded a calorific value of 19.2 ± 0.3 MJ/kg dry weight, while those from the Santa Rosa sugar factory recorded 17.0 ± 0.4 MJ/kg dry weight. Tests could not be performed on samples from the other mills.

In this way, and taking into account an average heating value, it is possible to determine the energy potential of both by-products. Table 2 shows the values of available dry biomass, average heating value, and calculated energy potential for sugarcane straw and bagasse.

Table 2. Energy potential of canal straw and sugarcane bagasse.

By-product	Dry biomass (t)	Average heating value (MJ/kg) (db)	Energy potential (GJ/y)
Canal straw	168 000	18.5	$3.11 \cdot 10^6$
Sugarcane bagasse	390 000	18.1	$7.06 \cdot 10^6$

Canal straw has an annual availability of approximately 168 000 tons of dry biomass, with an average calorific value of 18.5 MJ/kg, representing an energy potential of $3.11 \cdot 10^6$ GJ/year. Sugarcane bagasse, on the other hand, reaches a significantly higher volume, with 390 000 tons of dry biomass and an average calorific value of 18.1 MJ/kg, which translates into an energy potential of $7.06 \cdot 10^6$ GJ/year.

At the national level, the combination of canal straw and sugarcane bagasse can reach a potential of more than $10 \cdot 10^6$ GJ per year. This result is higher than that reported in Costa Rican sugar factories, where 200 000 dry tons generate approximately $3.8 \cdot 10^6$ GJ/year [25].

These results show that, although canal straw offers a slightly higher heating value, sugarcane bagasse provides more than twice the annual energy available, due to its higher production. This difference reflects the importance of considering both the intrinsic energy quality of each waste product and its actual availability in the territory when planning bioenergy systems.

Compared to other agricultural biomasses, the values obtained are competitive. For example, wheat straw usually has an average heating value of 15-17 MJ/kg [26], while rice straw, in addition to having a high ash content, reaches values of 13-15 MJ/kg [27]. In this sense, both sugarcane bagasse and cane bagasse are positioned as biofuels with higher energy quality. Likewise, the estimated energy potential of bagasse is similar to that reported for other large-scale agro-industrial wastes, such as corn stalks in producing regions [28].

Biomass characterization

Table 3 shows the characterization of the by-products studied.

Table 3. Biomass characterization.

		Canal straw	Sugarcane bagasse
Chemical analysis	Cellulose (%)	38.2 ± 1.6	43.4 ± 1.4
	Hemicellulose (%)	24.0 ± 1.2	27.3 ± 0.9
	Lignin (%)	20.4 ± 0.9	18.2 ± 0.8
Proximate analysis	Volatile matter (%)	80.0 ± 0.5	77.9 ± 0.5
	Fixed carbon (%)	15.2 ± 0.4	17.1 ± 0.7
	Ash (%)	4.8 ± 0.2	5.0 ± 0.3
Ultimate analysis	C (%)	45.8 ± 0.5	47.9 ± 0.4
	H (%)	5.5 ± 0.2	6.4 ± 0.2
	N (%)	0.9 ± 0.1	0.8 ± 0.1

The results show that sugarcane bagasse has a higher cellulose (43.4%) and hemicellulose (27.3%) content compared to canal straw (38.2% and 24.0%, respectively), making it a more favorable resource for biochemical conversion processes, such as enzymatic hydrolysis and bioethanol production. On the other hand, canal straw has a higher lignin content (20.4%), which implies a more recalcitrant structure and greater resistance to biological degradation, although this additional lignin fraction contributes to higher energy density and more stable combustion in thermochemical processes [28]. These values are similar to those reported for bagasse in Brazil (42-45% cellulose, 25-28% hemicellulose) and for lignocellulosic grasses in Asia (35-40% cellulose) [23] [29].

From an proximate analysis perspective, canal straw has a slightly higher volatile matter content (80.0% vs. 77.9%), which promotes rapid ignition and more intense release of combustible gases. In contrast, sugarcane bagasse has a higher fixed carbon content (17.1%), indicating more sustained and prolonged combustion. Both types of waste have moderate ash content (≈5%), lower than that reported for rice straw (15-20%), which reduces the problems associated with the formation of slag and deposits in combustion equipment [26] [27].

Ultimate analysis shows that sugarcane bagasse contains a higher percentage of carbon (47.9%) and hydrogen (6.4%), which translates into a higher heating value (HHV ≈ 16-17 MJ/kg), slightly higher than that of canal straw (≈15-16 MJ/kg). In both cases, the low nitrogen content (<1%) implies a low propensity for the formation of nitrogen oxides (NOx) during combustion, a key aspect in compliance with environmental regulations. These results coincide with analyses of sugarcane biomass in Cuba, where carbon accounts for 45% [30].

Compared to other agricultural biomasses, both materials have a competitive profile. Their structural carbohydrate content (cellulose + hemicellulose) exceeds that of rice straw and is similar to that of corn stalks, which reinforces their potential in biochemical processes. From a thermochemical point of view, the combination of a medium-high heating value with a moderate ash content positions both canal straw and sugarcane bagasse as attractive energy alternatives to other residual biomasses [31].

In summary, canal straw and sugarcane bagasse have complementary properties: the former stands out for its ease of ignition and higher lignin fraction, while the latter stands out for its higher cellulose fraction and heating value. The choice of one resource over the other will therefore depend on the type of conversion to be used: thermochemical processes in the case of canal straw and biochemical processes in the case of sugarcane bagasse.

CONCLUSIONS

This study shows that canal straw (*Saccharum spontaneum*) and sugarcane bagasse (*Saccharum officinarum*) are strategic resources for energy biomass production in Panama, with significant potential to diversify the energy matrix and mitigate the environmental impacts associated with their improper management.

The sustainable use of canal straw and bagasse not only reduces the carbon footprint, but also promotes the circular economy by transforming waste into value-added products, such as organic fertilizers from cogeneration ash and construction materials. However, there are significant challenges. Canal straw faces logistical limitations due to its low energy density, which increases collection and transportation costs, while bagasse requires adequate storage systems to prevent fermentation and the proliferation of pathogens [9] [14]. To overcome these barriers, it is recommended that public policies be implemented that include tax incentives for cogeneration, subsidies for mechanized straw collection, and regulations for the management of agro-industrial waste.

The comprehensive use of these resources positions Panama as a potential regional leader in biomass energy, following the example of other countries in the region, where cogeneration and sugarcane products have transformed the agro-industrial sector. The integration of cane straw and sugarcane bagasse into the energy mix will not only contribute to energy security but also generate socioeconomic benefits, such as job creation in the collection, processing, and marketing of derivative products. Future studies should focus on expanding national inventories of canal straw, optimizing energy conversion processes, and conducting economic evaluations of alternative uses to ensure large-scale viability.

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