



CIEEMAT | 2024

VIII Ibero-American Congress on Entrepreneurship, Energy, Environment, and Technology

Proceedings of the

CIEEMAT 2024

VIII Ibero-American Congress  
on Entrepreneurship, Energy,  
Environment, and Technology

Rio de Janeiro, Brazil  
October, 14-16, 2024



**Proceedings of the**

**CIEEMAT 2024 | VIII Ibero-American Congress on  
Entrepreneurship, Energy, Environment, and  
Technology**

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**Publisher**

Instituto Politécnico de Bragança (IPB)  
Campus de Santa Apolónia  
5300-253 Bragança - Portugal

December, 2024

ISBN: 978-972-745-349-8

Handle: <http://hdl.handle.net/10198/30674>

DOI: 10.34620/978-972-745-349-8

URL: <https://dippg.cefet-rj.br/ppges/index.php/pt/cieemat-principal>

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# About the Event

The Federal Center for Technological Education of Rio de Janeiro (CEFET/RJ), in collaboration with the Polytechnic Institute of Bragança (IPB), the Polytechnic Institute of Portalegre (IPPortalegre), and Petrobras, hosted the VIII Ibero-American Congress on Entrepreneurship, Energy, Environment, and Technology (CIEEMAT 2024). The event took place from October 14 to October 16, 2024, in Rio de Janeiro, Brazil.

With Energy Transition as its central theme, CIEEMAT 2024 fulfilled its founding mission: to strengthen Portuguese-Brazilian and Ibero-American cooperation in key areas such as energy efficiency, low-carbon hydrogen, electrification, and carbon capture, utilization, and storage. The event fostered international collaboration, enhancing partnerships between the organizing institutions and advancing global efforts in energy and environmental sustainability.

CIEEMAT 2024 provided a platform for discussing topics of critical importance to professionals in the energy transition sector. It also contributed significantly to the development of human resources, both nationally and internationally, by supporting education and training. Furthermore, the congress served as a practical step towards shaping public policies focused on sustainable development and social inclusion, addressing some of the most pressing challenges facing society today.

The CIEEMAT Congress has a 16-year history, hosting seven editions as a biennial event, playing a pivotal role for Ibero-American countries. Focused on topics in Entrepreneurship, Energy, Environment, and Technology, it serves as a bridge between academia, government, and industry. Its mission is to foster innovation and strengthen scientific collaboration with companies by analyzing opportunities and challenges posed by sectoral policies and tracking performance indicators for services and their impact.

First organized in 2015 by the Federal Center for Technological Education of Rio de Janeiro (CEFET/RJ), CIEEMAT has consistently addressed topics of national and global relevance. Its organization involves esteemed partners such as the Polytechnic Institute of Bragança (IPB), the Polytechnic Institute of Portalegre (IPPortalegre), the Secretariat of Professional and Technological Education (Setec) through the EnergIFE Program for Renewable Energy and Energy Efficiency in Federal Education Institutions, and Eletrobras/Eletronuclear.

CIEEMAT continues to provide a unique venue for the exchange of knowledge and collaborative solutions in energy and environmental challenges.

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# Scientific Program

14 October, Monday

Session #1 – Decarbonization and Climate Change		Room 513 Chair: Jaqueline Vieira
16:00-17:00	Energy Transition: The challenges in decarbonizing oil & gas production in Brazil <b>Milton Simas Gonçalves Torres</b> , Gustavo Castro Ribeiro, Hércules Souza de Medeiros and Luiz Philipe Martinez Marins	
	Sustainable Innovation Evaluation in Startups from the Centelha II Program in Mato Grosso do Sul <b>Fabrcio Privat</b> and Daduí Guerrieri	
	A systematic review and bibliometric analysis of life cycle assessment in public procurement Laíce Scotelano, <b>André Luiz Trajano</b> , Augusto Reis, Artur Jorge Gonçalves and Ronney Boly	
Session #2 – Decarbonization and Climate Change		Room 513 Chair: Laene Soares
17:00-18:00	Utilization of Excess Energy in Photovoltaic Plants Caused by Clipping: Efficiency Comparison between Battery and Green Hydrogen Storage Solutions Beatriz Horn, Orlando Soares and <b>Paulo Brito</b>	
	Metal phosphates electrocatalysts applied for hydrogen evolution reaction <b>Jose Antonio Rodrigues</b> , João Victor Moraes, Thomaz Barros, Suresh Rajendran and Ana Lucia de Barros	
	Hydrothermal synthesis of copper cobalt oxide nanosheets for efficient electrocatalytic hydrogen generation <b>Sasikumar Yesudass</b> , Suresh Babu Rajendran, José Antonio Rodrigues and Ana Lucia de Barros	
Session #3 – Renewable energies		Room 515 Chair: Daniel Penalva Santos
16:00-17:00	Transitioning Santiago Island to a Renewable Energy Based system Cintia Garcia, Luís Lopes, Gabriel Roma and <b>Ângela Ferreira</b>	
	A Context-Aware Approach to Data Exchange in the Energy Sector <b>Matheus Jenevain</b> , Mario Dantas, Laís Berno and Milena Pinto	
	Economic Viability Analysis of Photovoltaic Systems in the Residential Sector in Brazil and Portugal Gabriel Marques, Beatriz Horn, <b>Thiago Americano Do Brasil</b> and Orlando Soares	
	The Wind Energy Market and the Institutional Influences of Non-Market Strategy in the Northeast Region – A Case Study on Enel Green Power <b>Ricardo Nascimento Ferreira</b> and Paula Cristina Afonso dos Ferreira	
Session #4 – Renewable energies		Room 515 Chair: Yasmim Chaves
17:00-18:00	Facile electro-co-polymerization of polyaniline- poly(3,4-ethylenedioxythiophene) on flexible carbon fiber electrodes for supercapacitor applications <b>Alberto Matheus da Silva Rangel</b> , Monique Pacheco Do Amaral, Vernan da Silva Lima, Leandro Samyn, Rejendran Suresh Babu, Diego Barreto Haddad and Ana Lucia de Barros	
	Biogas Purification from Landfill Gas by Adsorption <b>Janks Karbdala Leal de Paiva</b> , José Antônio Correia Silva and Ronney Arismel Mancebo Boly	
	Evaluation of an ARIMA model for forecasting distributed generation installed power <b>Tiago A. Silva</b> and Daduí C. Guerrieri.	
	Evaluation of Photovoltaic Performance in DSSCs Through Fe2O3 Doping in TiO2 Electrodes Sensitized by Organic Dyes <b>Higor Oliveira da Cunha</b> , Arcano Matheus Bragança Leite, Rajendran Suresh Babu, Diego Barreto Haddad and Ana Lucia Ferreira de Barros	

## 15 October, Tuesday

<b>Session #5 – Decarbonization and Climate Change</b>		<b>Room 513 Chair: Laene Soares</b>
16:00-17:00	Systematic Literature Review of Low-Carbon Hydrogen: Encompassing ESSG Perspectives Fabiana de Oliveira Ramos, <b>Daniel De Cerqueira Lima E Penalva Santos</b> and Ronney Arismel Mancebo Boly	
	Analysis of Low-Carbon Hydrogen Production in Landfills <b>Brenda dos Santos Costa</b> , Laene Oliveira Soares, Daniel De Cerqueira, Lima e Penalva Santos, Anna Paula Bourdon and Ronney Arismel Mancebo Boly	
	Synthesis of Nanostructured Perovskite for Intermediate-temperature Solid Oxide Fuel Cell <b>Nivaldo José da Silva</b> , Clara Lechtman Gazel and Marcello Dumont	
	Municipal Solid Waste Biorefineries: A Systematic Literature Review <b>Yasmim Aparecida de Oliveira Chaves</b> , Maria Margarida B. P. Gonçalves, Pedro Romano and Ronney Arismel Mancebo Boly	
<b>Session #6 – Sustainable Urban Mobility</b>		<b>Room 513 Chair: Danielle Rodrigues</b>
17:00-18:00	Eco-Efficiency and Economic Assessment of Electric Vehicle Technologies <b>Laene Oliveira Soares</b> , José Ricardo Sodr�, Luis Hern�ndez-Callejo and Ronney Boly	
	Carbon policies and electric vehicles: a systematic review of the main strategies <b>Eyko Medeiros Rios</b> , Wallice Medeiros de Souza, Pedro Henrique Gonz�lez Silva and Vanessa de Almeida Guimar�es	
	Analysis of the Integration of Sustainability Education in the Engineering Curriculum at a Federal Educational Institution in Brazil <b>Ezequiel Oliveira</b> , Pedro Gonz�lez and Vanessa de Almeida Guimar�es	
	Incorporating Sustainability in Engineering Education: A Literature Review <b>Ezequiel Oliveira</b> , Pedro Gonz�lez and Vanessa de Almeida Guimar�es	
<b>Session #7 – Renewable energies</b>		<b>Room 515 Chair: Carlos Eduardo Corr�a</b>
16:00-17:00	Supply Chain Management of Photovoltaic Modules: State of the Art Through Prisma Margarete Heleno, <b>Udneli Rodrigues</b> , Gisele Vieira, Anna Paula Bourdon and Ronney Arismel	
	Comparative Analysis on the Energy Markets of Portugal and Brazil Danilo S. Saes, Jo�o Pedro L. Bressiani and <b>Rubipiara C. Fernandes</b> .	
	A comparison review of levelized cost of hydrogen produced from renewable sources <b>Leonardo Kattah</b> , Rubipiara Cavalcante Fernandes and Edison Antonio Cardoso Aranha Neto	
	Life cycle assessment in energy recovery from municipal solid waste: A bibliometric analysis and systematic review <b>Gard�nia Mendes de Assun�o</b> , Doralice Chagas Tavares and Ronney Arismel Mancebo Boly	
<b>Session #8 – Renewable energies</b>		<b>Room 515 Chair: Yasmim Chaves</b>
17:00-18:00	Comparative Analysis of Low-Carbon Hydrogen Industrial Plants, Based on Environmental Impact Studies <b>Paulo Marcos Cabral Junior</b> , Paulo S�rgio Rosa Fernandes and Guilherme Amaral Do Prado Campos	
Biomass feeding systems – are we ready to run cellulosic ethanol plants? <b>Carlos E. F. Corr�a</b> , Daniel De Cerqueira Lima e Penalva Santos, Jos� V. Bomtempo, Flavia C. Alves, Cristina G. Souza and Ronney A. M. Boly		

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# Energy Transition: The challenges in decarbonizing oil & gas production in Brazil

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## Abstract

The article discusses the opportunities and challenges that exist in the exploration and production of oil and gas (O&G) fields, aiming to reduce greenhouse gas emissions in this O&G extraction in Brazil. The article highlights the opportunities and challenges with a focus on studying the heterogeneity of the oil & gas sector in the adoption of sustainable practices, in production in O&G fields at sea (offshore), existing systems in surface production facilities (offshore platforms) and the possible use of renewable energy on these offshore platforms.

## 1. Introduction

The oil and gas industry is facing significant challenges in transitioning to more sustainable practices. There is notable variation among companies in the sector regarding the adoption of energy management and carbon neutrality practices, reflecting different approaches to sustainability. Key initiatives in this context include standardization and the establishment of sustainability benchmarks led by organizations like the International Organization for Standardization (ISO) and the International Association of Oil and Gas Producers (IOGP). ISO has developed the ISO 50001 standard, which provides a comprehensive framework for implementing and improving Energy Management Systems (EMS), promoting energy efficiency and reducing greenhouse gas (GHG) emissions. ISO Technical Committee 207/SC 7 focuses on standardizing GHG emissions and adapting to climate change effects, aiming to effectively reduce emissions and enhance adaptation strategies.

Other important initiatives include the International Petroleum Industry Environmental Conservation Association (IPIECA) and the Oil and Gas Climate Initiative (OGCI), which play vital roles in promoting sustainable practices. These efforts reflect a coordinated approach to standardizing sustainability practices in the oil and gas sector, offering clear guidelines and benchmarks to enhance energy and carbon management practices.

Additionally, electricity generation on offshore oil and gas platforms is a significant source of CO<sub>2</sub> emissions. The integration of renewable energy sources, such as offshore wind energy, can contribute to reducing these emissions. Combining gas turbines with renewable energy technologies and utilizing

energy storage systems can improve energy efficiency and reduce reliance on fossil fuels, fostering more sustainable practices.

Furthermore, the use of digital tools in engineering projects for offshore oil and gas units can optimize energy efficiency and minimize atmospheric emissions. These tools enable the optimization of energy usage across different processes, the utilization of waste heat from turbogenerators, and the optimization of heat exchanger utilization. In summary, the oil and gas industry is actively seeking sustainable solutions to reduce greenhouse gas emissions and enhance energy efficiency in offshore operations.

## 2. The heterogeneity of the oil & gas sector in the adoption of sustainable practices among companies

The oil and gas (O&G) sector faces a significant challenge in its transition to more sustainable practices. Within the industry, there is notable variability in the adoption of energy management and carbon neutrality practices, reflecting a heterogeneous approach to sustainability. While some companies are leading advanced initiatives, others are still in the early stages of integrating these practices into their operations.

One of the most important initiatives in this context is the standardization and creation of sustainability benchmark criteria, spearheaded by organizations such as the International Organization for Standardization (ISO) and the International Association of Oil & Gas Producers (IOGP). The ISO Technical Committee 301 (ISO TC 301) plays a key role in developing international standards that address energy management challenges across various sectors. For example, the ISO 50001 standard provides a robust framework for establishing, implementing, maintaining, and improving an Energy Management System (EMS) (ISO, 2018). This standard is crucial for the O&G sector as it promotes a comprehensive approach that integrates existing systems, facilitates improvements in energy efficiency, and reduces greenhouse gas (GHG) emissions (Souza Lira et al., 2019).

Additionally, ISO Technical Committee 207/SC 7 focuses on standardizing GHG emissions and developing strategies for adapting to the effects of climate change, by creating standards aimed at effectively reducing GHG emissions and improving adaptation strategies (ISO, 2024). The ISO 14060 series complements these efforts by transforming scientific knowledge into practical tools to combat climate change, with a focus on the quantification, monitoring, reporting, validation, and verification of GHG emissions and removals (ISO, 2023a).

In the context of O&G, ISO Technical Committee 67 (ISO/TC 67) harmonizes and manages specific global standards for the industry, aiming to achieve international conformity for the sector's products (ISO, 2023b). Additionally, organizations such as the International Petroleum Industry Environmental Conservation Association (IPIECA) and the IOGP have played vital roles in promoting sustainable practices. Since its founding in 1974, IPIECA has guided the sector on environmental and social issues, expanding its scope over the years to include a wide range of sustainable practices (United Nations, 2023). IOGP, in turn, serves as a forum for the upstream industry, addressing areas such as safety, health, and the environment, and more recently, energy transitions (IOGP, 2023).

Another notable initiative is the Oil and Gas Climate Initiative (OGCI), a CEO-led consortium that brings together some of the world's largest O&G companies to lead the sector's climate response. OGCI created OGCI Climate Investments, a fund exceeding \$1 billion, aimed at investing in technological innovations and projects that accelerate decarbonization (Climate Initiatives Platform, 2022).

These initiatives reflect a coordinated effort to standardize sustainability practices in the O&G sector, providing clear guidelines and benchmarks to help companies improve their energy and carbon management practices. Despite variations in the adoption of these practices among companies, these

standards and initiatives offer a structured path to the energy transition, promoting energy efficiency and reducing GHG emissions across the industry. A summary of the initiatives is presented in Table 1.

<b>Title</b>	<b>Purpose</b>	<b>Issuer</b>
ISO 50001 - Energy management	Provides a framework for establishing, implementing, maintaining, and improving an Energy Management System (EMS)	International Organization for Standardization (ISO)
ISO/TC 207/SC 7	Standardizes greenhouse gas emissions and adaptation to climate change, creating standards to effectively reduce emissions and improve adaptation strategies	International Organization for Standardization (ISO)
ISO/TC 67 (ISO/TC 67)	Harmonizes and manages specific global standards for the oil and gas industry, aiming for international conformity for the sector's products	International Organization for Standardization (ISO)
International Petroleum Industry Environmental Conservation Association (IPIECA)	Guides the oil and gas sector on environmental and social issues, expanding its scope to include a wide range of sustainable practices	International Petroleum Industry Environmental Conservation Association (IPIECA)
Oil and Gas Climate Initiative (OGCI)	Leads the sector's climate response by bringing together some of the world's largest oil and gas companies. Created OGCI Climate Investments, a fund aimed at investing in technological innovations and projects that accelerate decarbonization	Oil and Gas Climate Initiative (OGCI)

**Table 1:** Documents for sustainability benchmark criteria in O&G production- source: authors

### 3. Offenders of greenhouse gas emissions in O&G production on offshore platforms

Offshore oil and gas (O&G) production significantly contributes to greenhouse gas (GHG) emissions through flaring, venting, combustion for power generation, logistics, and fugitive emissions. These emissions include both CO<sub>2</sub> and methane, with methane having a much higher global warming potential. Efforts to mitigate these emissions focus on improving efficiency, capturing and utilizing associated gas, and transitioning to low-carbon energy sources. The primary sources of GHG emissions in offshore oil and gas production are associated with key activities and can be categorized as follows:

### 3.1. Flaring and Venting

- **Flaring** involves the burning of excess natural gas that cannot be processed for various reasons, producing CO<sub>2</sub>. Flaring in offshore oil and gas production is typically categorized as routine, non-routine, and emergency/safety flaring.
- **Venting** is the direct release of natural gas into the atmosphere, predominantly consisting of methane (CH<sub>4</sub>), a potent greenhouse gas with a global warming potential significantly higher than CO<sub>2</sub>. Some offshore operations, mainly venting from Floating Production Storage and Offloading (FPSO) cargo tanks, can generate substantial GHG emissions.

Routine flaring is a major source of GHG emissions in offshore oil and gas production, accounting for about 60-70% of total emissions (IEA, 2021). It is crucial to distinguish between different types of flaring to develop effective reduction strategies and enhance the environmental performance of offshore activities. Oil and gas companies are working to eliminate venting, cease routine flaring, and significantly reduce irregular flaring. The introduction of closed flare systems with new technology aims to cut flaring by 70 to 80% (IEA, 2021).

### 3.2. Power Generation Emissions on Offshore Platforms

Power generation is a dominant source of CO<sub>2</sub> emissions on offshore O&G platforms, accounting for around 60% of global emissions (IPIECA-IOGP, 2022). These emissions vary due to regional differences in technology, regulatory frameworks, and operational practices, including:

- **Energy-Intensive Operations: Offshore platforms require continuous energy for drilling, production, processing, and other activities. This energy is predominantly generated using gas turbines or diesel generators, both of which are major sources of CO<sub>2</sub> emissions.**
- **Limited or No Access to the Grid: Unlike onshore facilities, offshore platforms typically do not have access to grid electricity and must generate power on-site. Some platforms, particularly in the North Sea, are now linked to alternative energy sources from the continental grid. This connection, along with the development of power generation hubs to produce and distribute energy and capture CO<sub>2</sub>, is a potential solution for reducing emissions.**
- **Operational Efficiency and Technology: Even with stringent regulations and high operational efficiency standards, on-site power generation still primarily relies on fossil fuels. Efficient gas turbines produce substantial emissions due to the large amounts of energy required.**

The efficiency of offshore gas turbines is influenced by design features, operational conditions, maintenance practices, and technological advancements, all of which directly impact emissions. Improving efficiency involves optimizing load factors, maintaining turbines regularly, utilizing advanced control systems, and integrating renewable energy sources. By focusing on these areas, offshore platforms can significantly reduce CO<sub>2</sub> emissions and enhance overall sustainability.

Gas turbines are a critical component of power generation on offshore oil and gas platforms, providing the necessary electricity and mechanical power for various operations. Their efficiency can vary based on several factors:

- **Design and Technology:** Contemporary turbines are equipped with sophisticated aerodynamic designs that minimize air resistance and improve operational efficiency. Advanced cooling methods, using progressive materials and cooling by air or steam, enable turbines to operate at elevated temperatures, enhancing thermal efficiency. The integration of Combined Cycle Gas Turbine (CCGT) systems, which use waste heat from the gas turbine to generate additional electricity via a steam turbine, can boost overall efficiency to over 60% (IPIECA-IOGP, 2022).
- **Operational Conditions:** Effective operation hinges on maintaining a high load factor. Gas turbines operate most efficiently at or near their full load capacity. Running at partial capacity reduces efficiency due to less optimal combustion and greater proportional heat loss. The type and quality of fuel are crucial, with natural gas often favored for its clean burn and compatibility with offshore well output. However, the use of innovative fuels like hydrogen (H<sub>2</sub>) and ammonia (NH<sub>3</sub>) in gas turbines is rapidly progressing, although still at the forefront of technology.
- **Enhancements in Maintenance and Operation:** Improving routine maintenance schedules and adopting predictive maintenance based on real-time conditions are essential for optimizing power generation availability. Fine-tuning operational strategies, such as managing spinning reserves and applying intelligent load management to keep turbines operating within their ideal range, increases efficiency.
- **Technological Innovations:** Utilizing sophisticated control systems and algorithms can optimize turbine operation by adjusting parameters in real time to maintain optimal efficiency. Leveraging predictive analytics and machine learning to forecast maintenance needs and optimize operational parameters can enhance efficiency and reliability.
- **Hybrid Solutions:** Integrating gas turbines with renewable energy technologies can improve the efficiency of energy consumption and reduce dependence on fossil fuels, contributing to more sustainable practices. The introduction of battery energy storage systems (BESS) can capture surplus energy and level out demand spikes, keeping turbines operating within their most efficient range.

In general, simple cycle gas turbines have 25-40% thermal efficiency (EERE, 2023), depending on the model and operational conditions. If configured as combined cycle gas turbines, this efficiency can reach up to 60%, achieved by utilizing waste heat for additional power generation. In this configuration, there is an opportunity to reduce overall GHG emissions by up to 25% on an offshore O&G platform operating with natural gas (EERE, 2023).

To understand how these efficiencies translate into CO<sub>2</sub> emissions, consider a gas turbine with an efficiency of 35% operating in simple cycle mode:

- 1) Energy Content of Natural Gas: ~ 50 MJ/kg.
- 2) CO<sub>2</sub> Emission Factor for Natural Gas: ~2.75 kg CO<sub>2</sub>/kg of natural gas.

If the turbine generates 1 MWh (3.6 GJ) of electricity:

3) Fuel Required:  $\frac{3.6 \text{ GJ}}{0.35} \approx 10.29 \text{ GJ}$

4) Natural Gas Required:  $\frac{10.29 \text{ GJ}}{50 \frac{\text{MJ}}{\text{kg}}} \approx 205.8 \text{ kg}$

5) CO<sub>2</sub> Emissions:  $205.8 \text{ kg} \times 2.75 \frac{\text{CO}_2}{\text{kg}} \approx 566 \text{ kg CO}_2 / \text{MWh}$

**Note:** the energy content of 1 Boe is approximately 5.8 MMBtu, which is roughly 1.7 MWh. Thus, CO<sub>2</sub> emissions per Boe can be calculated as:

6)  $1.7 \text{ MWh} \times 566 \frac{\text{kg CO}_2}{\text{MWh}} = 962.2 \text{ kg CO}_2 / \text{Boe}$

If a platform generates 657,000 MWh of electricity annually, equivalent a 75 MWh of power generation, the CO<sub>2</sub> emissions would be:

7)  $657,000 \text{ MWh} \times 566 \text{ kg CO}_2 / \text{MWh} = 371,862,000 \text{ kg CO}_2$  or 371,9 Mt CO<sub>2</sub> per year.

## 4. Renewable energies in O&G offshore E&P

As mentioned earlier, a key factor in the decarbonization of offshore oil and gas (O&G) exploration and production (E&P) in Brazil is the generation of electrical energy. The most common method for generating electricity on offshore E&P platforms is through gas turbine generators, which are typically responsible for more than 70% of total emissions (IEA, 2021).

One potential solution to address this challenge is the integration of renewable energy sources in offshore O&G fields. The most technologically mature option is the use of offshore wind power to reduce greenhouse gas (GHG) emissions from offshore extraction activities. This can be achieved in the following ways:

- Direct Connection of Offshore Wind Power: Directly connecting offshore wind power to the platform's electrical power generation system.
- Powering Submarine Systems: Using offshore wind power to supply energy to submarine systems that are currently powered by the platform's electrical power.

However, there are several technological challenges specific to the offshore environment that must be addressed for the successful integration of wind turbines. Research, development, and innovation projects are required to overcome these challenges. The key technological challenges related to offshore wind power generation can be summarized as follows (McLaurin et al., 2021; Konstantinidis et al., 2016):

- Maritime Support Structure: Offshore wind turbines require a robust support structure to remain secure and stable in the marine environment. These structures must be designed to withstand adverse conditions, such as strong winds, ocean currents, and high waves.

Additionally, they must accommodate the wind power cables and provide a safe base for the turbines.

- Energy Transport - Electrical Cables:
  - Cable Technologies: Offshore wind power systems require cables capable of transmitting energy from the turbines to the E&P platforms. These cables must be designed to withstand the dynamic conditions of the marine environment, including wave and current movements, and must be capable of handling high voltages while remaining safe to operate.
  - Cable Configuration and Routing: Determining the optimal configuration and routing of energy transport cables is another challenge. This involves deciding how cables will be positioned on the seabed and connected to offshore facilities. Proper configuration and routing are essential to ensure efficient and reliable energy transmission.
- Generator Sizing: The size and capacity of the generators used in wind turbines can significantly impact the performance of the entire system. The offshore environment has unique characteristics compared to the onshore environment, where wind power generation is more established. Therefore, specific studies are necessary to determine the appropriate size and capacity of each generator for offshore use.
- Energy Storage Optimization: Given the varying electrical loads in the offshore environment, it is essential to explore the most effective ways to store energy generated by wind turbines. This includes considering load volatility, random anomalies, and frequency irregularities.

To address these existing technological challenges associated with offshore wind power, a systematic process is needed to identify, evaluate, and, where possible, quantify these challenges. A more in-depth analysis of the viability of offshore wind energy in Brazil's unique marine conditions is an extremely complex topic as it encompasses variables such as geotechnical surveys, wind maps and logistical chains. These factors will enable a comparative analysis of the costs and benefits of integrating offshore wind energy.

## 5. Digital tools for Offshore E&P Units (Platforms) Focused on Energy Efficiency and Reduction of Atmospheric Emissions

In developing engineering projects for offshore oil and gas (O&G) exploration and production (E&P) units, whether for new fields or the revitalization of existing ones, there are several challenges due to the complexity and broad scope of these stationary production units (platforms). Additionally, it is essential to evaluate these projects considering initiatives aimed at improving energy efficiency and reducing atmospheric emissions. Key initiatives in this regard include (Hwang et al., 2009):

- Energy Optimization Among Process Streams: This involves harnessing the thermal potential of various process streams within these units to reduce the demand for hot and cold utilities, resulting in overall energy gains for the platform.

- **Utilization of Waste Heat from Exhaust Gases:** Waste heat from the exhaust gases of turbogenerators can be used for oil processing, which reduces the demand for hot utilities and contributes to the energy efficiency of the oil separation and treatment system. Additionally, efforts should focus on minimizing the thermal load and evaluating the return of produced water or hot oil to the separation system to improve process efficiency.
- **Optimization of Heat Exchanger Usage:** Improving the use of heat exchangers by minimizing temperature differences between hot and cold sources and reducing pressure losses is another way to enhance energy efficiency. When specifying heat exchangers, factors such as the degradation of energy efficiency over their lifecycle, the types of fluids involved, and pressure drops should be considered.

These initiatives can bring substantial energy efficiency gains and reduce atmospheric emissions on O&G offshore E&P platforms. However, implementing these initiatives may present difficulties during the engineering design phase and throughout the platform's operational lifespan. To help overcome these challenges, the use of digital tools becomes essential as soon as possible. One such tool is the utilization of dynamic simulators for both processes and equipment (Thiabaud et al., 2011). Opportunities for using dynamic process simulators integrated with equipment simulators to improve energy efficiency and reduce GHG emissions include:

- **Energy Optimization Among Process Streams:** Dynamic process and equipment simulators can be used to analyze and optimize energy flow among different process streams, harnessing thermal potential and reducing the demand for hot and cold utilities. The systems and equipment involved in this simulation include heat exchangers, pumps, compressors, and other thermal energy transfer devices.
- **Utilization of Waste Heat and Optimization of Oil Processing:** Dynamic simulation can be employed to analyze and optimize the use of waste heat from turbogenerator exhaust gases for oil processing, allowing for the optimization of heating fluid temperatures. It also facilitates the sizing of oil separation and treatment processes to minimize thermal load and assess the return of produced water or hot oil to the separation system. The systems and equipment involved in this simulation include turbogenerators, heat exchangers, heating systems, separators, treaters, and other oil processing equipment.
- **Specification of Heat Exchangers:** Using equipment simulators enables the specification of heat exchangers according to process needs, considering factors such as degradation of energy efficiency over the platform's lifecycle, the fluids involved, and pressure drop. The systems and equipment involved in this simulation include heat exchangers and heat transfer pipelines.
- **Minimization of Temperature Differences and Pressure Losses in Heat Exchangers:** Dynamic simulation allows for the analysis and optimization of heat exchanger sizing, taking into account factors like energy efficiency degradation over time, the fluids involved, and pressure drops. This contributes to the overall energy efficiency of the system. The systems and equipment involved in this simulation are heat exchangers and heat transfer pipelines.

Another potential application of digital tools in the pursuit of energy efficiency and reduction of GHG emissions on offshore E&P platforms is the use of Large Language Models (LLMs) throughout

the entire lifecycle of the platforms to evaluate engineering design efficiency. By inputting information about the O&G to be processed (such as API gravity, Gas-Oil Ratio (GOR), liquid and gas flow rates, inlet temperature, and contaminants like H<sub>2</sub>S and CO<sub>2</sub>) and leveraging knowledge from previously executed projects on other units, it is possible to generate outputs focused on energy efficiency and GHG emission reduction. These outputs may include proposals for the (re)definition of the plant, with process flow diagrams, dimensions, and key equipment capacities (e.g., vessels, heat exchangers, large compressors, pumps) as well as a layout with the optimized placement of this equipment (Thatcher et al., 2024).

## 6. Conclusions

The transition to a more sustainable energy landscape within Brazil's offshore oil and gas (O&G) exploration and production (E&P) industry presents both significant challenges and promising opportunities. The industry's diverse approach to adopting sustainable practices highlights the need for standardized benchmarks and frameworks, such as those provided by ISO and O&G associations, to guide companies toward energy efficiency and carbon neutrality. These standards are essential tools for harmonizing efforts across the sector and promoting a unified approach to sustainability.

The predominant role of power generation emissions, particularly from gas turbine generators, in contributing to greenhouse gas (GHG) emissions on offshore platforms cannot be overstated. Innovative solutions like carbon capture, utilization, and storage (CCUS) and the integration of Combined Cycle systems offer promising pathways to enhance efficiency and reduce emissions. Additionally, transitioning to renewable energy sources, particularly offshore wind power, stands out as a viable alternative with significantly lower emissions. The technological advancements and ongoing research in offshore wind power generation are crucial to overcoming the specific challenges of operating in the marine environment.

Digital tools and dynamic simulators are also essential in optimizing energy use and minimizing emissions throughout the lifecycle of offshore platforms. These tools enable precise modeling and simulation of processes and equipment, leading to better design, improved operational efficiency, and more effective energy management. Integrating these digital solutions with advancements in large language models (LLMs) can further revolutionize engineering design and operational strategies, driving the sector toward greater sustainability.

While the path to decarbonizing Brazil's offshore O&G operations is challenging, it offers significant opportunities for innovation and progress. Through the combined efforts of industry stakeholders, guided by robust standards, supportive policies, and powered by cutting-edge technologies, the sector can achieve substantial reductions in its carbon footprint. This transition not only aligns with global climate goals but also strengthens the economic and environmental sustainability of Brazil's O&G industry. Moving forward, a collaborative approach, continuous innovation, and a steadfast commitment to sustainability will be crucial in achieving these objectives.

### **Future Directions and Policy Recommendations**

- **Strengthening Regulatory Frameworks:** The government should establish clear and enforceable regulations that require offshore O&G companies to adopt energy-efficient technologies and practices. This could include mandates for routine flaring reductions, incentives for implementing CCUS, and requirements for incorporating renewable energy sources such as offshore wind power.

- Promoting Technological Innovation: Increased investment in research and development (R&D) for technologies such as combined cycle gas turbines, closed flare systems, and hybrid energy solutions that integrate renewables with existing infrastructure should be prioritized. Public-private partnerships can help to advance these innovations, reducing costs and accelerating their deployment.
- Facilitating the Adoption of Digital Tools: Encourage the use of digital tools, such as dynamic simulators and artificial intelligence, through tax incentives, grants, or subsidies. These tools can help optimize energy use, reduce emissions, and improve overall platform efficiency. Additionally, the development of digital twins for offshore platforms should be supported to enable real-time monitoring and predictive maintenance.
- Establishing Renewable Energy Integration Targets: Set specific targets for integrating renewable energy sources, like offshore wind, into the power supply of O&G offshore operations. This could include establishing a timeline for phasing in renewables and offering financial incentives for early adopters. The government should also support grid connections to offshore wind farms to facilitate their use in powering platforms.
- Implementing Transparent Reporting and Benchmarking: Introduce mandatory reporting requirements for GHG emissions and energy efficiency metrics. This will help create transparency, allow for benchmarking against industry standards, and provide data to track progress toward decarbonization goals.

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# Sustainable Innovation Evaluation in Startups from the Centelha II Program in Mato Grosso do Sul

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## Abstract

This study analyses the perceptions of entrepreneurs and mentors participating in the Centelha II Program in Mato Grosso do Sul, focusing on the sustainable innovation practices adopted by the startups and the main challenges faced during the development and implementation of their solutions. Using a field research approach, a structured questionnaire was applied to 28 startup entrepreneurs, followed by a semi-structured interview with 12 mentors responsible for accompanying this group. The results reveal a diversity of innovative solutions in areas such as biotechnology, advanced manufacturing, and others, and they also highlight significant disparities between the evaluations of entrepreneurs and mentors. While the entrepreneurs believe that their solutions contribute to reducing environmental impacts, the mentors present a different view, in which the startups are perceived to have low clarity in their vision and mission. Despite the entrepreneurs' confidence in their growth strategies, the perceptions of mentors and startups indicate the urgent need for more robust approaches to overcome these challenges. This study suggests the necessity for greater alignment between the innovation perception and the market reality, as well as strengthening academic partnerships and product development strategies to ensure the success of startups.

Keywords: Sustainable innovation, startups, Centelha II Program, Mato Grosso do Sul

## 1. Introduction

The Centelha Program promotes innovative entrepreneurship in Brazil, offering financial support, training, and mentoring for the creation of startups. The program is aimed at undergraduate and graduate students, technicians, and professionals from state-owned or private companies with innovative ideas for products, services, or industrial processes (MINISTRY OF SCIENCE, TECHNOLOGY AND INNOVATION, 2021).

Organised at the state level, the program is run by the Research Support Foundation of each Brazilian state, which in Mato Grosso do Sul is run by FUNDECT (Foundation for Supporting the Development of Education, Science, and Technology in the State of Mato Grosso do Sul), with calls for proposals.

The main objective of the Centelha Program is to transform innovative ideas into viable startups, which can develop products, services, or improvements in industrial processes. These solutions must be creative and differentiated, capable of capturing market interest, whether local or not, to provide

useful innovative solutions for various types of clients, including citizens, companies, government bodies, and other institutions.

Participants in the program receive intensive training and financial support. The program's methodology is based on a practice that has been proven over a decade, initially developed by the CERTI Foundation (2023) in Florianópolis. This methodology has effectively brought university entrepreneurs with advanced technologies to the market in nanotechnology, digital convergence, medical instrumentation, and solutions for industry and agriculture (FUNDECT, 2021).

At the end of the program, entrepreneurs have access to additional opportunities, such as incubators, technology parks, and innovation centres that offer continuous support. The program integrates participants into an innovation ecosystem, facilitating contact with partners, investors, and the market, thus accelerating the development of their initiatives. This support aims to provide significant sustainable development, aligning with Brazil's technological and economic advancement objectives.

With this in mind, field research was conducted with a sample of 28 startups participating in the Centelha II Program and 12 innovation mentors responsible for accompanying these startups during their journey through the program. Thus, this study aims to analyse the perceptions and evaluations of startup entrepreneurs and mentors participating in the Centelha II Program in Mato Grosso do Sul, focusing on solutions that might mitigate environmental impacts. Additionally, it evaluates the main challenges and obstacles faced during the development and implementation process of the solutions.

The justification for this study lies in the importance of understanding the dynamics and challenges faced by startups in innovation programs such as Centelha II. Disparities in the perceptions of entrepreneurs and mentors can reveal critical areas that need improvement and additional support. In addition, a detailed analysis of these dynamics can contribute to formulating more effective policies and strategies to support sustainable innovation and the growth of startups in Mato Grosso do Sul and other regions.

## 2. Startups and Sustainable Innovation in the Context of the Centelha II Program

The role of startups as agents of socio-environmental innovation has gained prominence in academic literature and public policy (INOVATIVA, 2024). Startups are often defined as temporary organisations searching for a scalable and repeatable business model (BLANK; DOLF, 2022). Eric Ries (2011) describes a startup as an organisation created to develop a new product and/or service under extreme uncertainty conditions. These definitions emphasise the flexibility and adaptability of startups, essential characteristics for implementing innovative solutions.

According to Boons and Lüdeke-Freund (2013), sustainable innovation involves the creation of new products, processes, or business models that bring advantages to the environment, society, and the economy. This concept is essential for startups seeking not just profit but also positive social and environmental transformation. Hansen and Schaltegger (2016) also reinforce that sustainable innovation has the potential to create value not just from an economic perspective but also from environmental and social aspects.

Participating startups are encouraged to develop solutions that mitigate environmental impacts in the context of the Centelha Program, which aims to promote innovative entrepreneurship. To achieve this, the program offers financial support, training, and mentorship intending to transform ideas into viable businesses (FUNDECT, 2021). This support is crucial in overcoming the challenges often faced by startups, such as the lack of resources and adequate technical support (BLANK; DOLF, 2022).

Among the program's resources, mentors support startups, especially in the final phase of their projects. Direct and continuous contact with mentors is one of the ways how startups can overcome challenges and improve their sustainable innovation practices (MAO *et al.*, 2011).

According to Cull (2006), the mentor facilitates change and guides the entrepreneur, preventing mistakes that could compromise business growth. A good mentor is influential, possesses advanced knowledge, and is committed to supporting the entrepreneur, who must be dedicated to their development (RONSONI; GUARESCHI, 2018).

Silva *et al.* (2024) suggest that mentoring should be customised to the specific needs of each company to maximise its benefits. Calvosa (2017) emphasises that these benefits include greater openness to change, stimulation of creativity, workplace innovation, and better harmony between personal and professional development.

### 3. Methodology

This article describes some challenges faced in the search for innovative solutions presented by startups participating in the Centelha II Program in Mato Grosso do Sul. To this end, a field research approach was used; it focuses on investigation by collecting information and knowledge, intending to obtain answers to hypotheses about phenomena that may impact a population (LAKATOR; MARCOLI, 2003).

The sample used in the research included 28 of the 50 startups participating in the Centelha II Program in Mato Grosso do Sul. They spontaneously chose to answer a quantitative analysis survey to measure specific points of the solutions they expected to introduce into the market. Explanatory analyses in survey research aim to develop general propositions about human behaviour (BABBIE, 1999), presenting the opinions of individuals from a specific population to explain an occurrence.

Before collecting the data, the mentors who accompanied this sample told the entrepreneurs responsible for the startups that the questionnaire would be used to measure their progress within the program. After this explanation, data collection began sending the access link to the electronic questionnaire, hosted on Google Forms, containing ten structured questions. Data was collected between June 3 and June 18, 2024.

Once the initial data was available, statistical analysis was performed using Excel 365 tools. The results were recorded and served as the basis for drawing up a second questionnaire, which was applied to the mentors who accompanied the startups in the sample.

In this second phase, a semi-structured interview was conducted with 12 mentors regarding the 28 startups they were following. The data collection was performed in the form of online interviews, with an average duration of 40 minutes, between June 25 and July 4, 2024.

The responses collected during both phases served as the basis for comparing the entrepreneurs' perceptions of their solutions with the mentors' evaluations regarding the consistency of the responses obtained.

### 4. Results and Discussions

The 50 startups participating in the Centelha II Program in Mato Grosso do Sul present a wide variety of themes, reflecting the diversity and innovative potential of the local ecosystem. Data analysis reveals that "Biotechnology and Genetics" is the most predominant area, having 11 startups working in this field. Graph 1 describes the other themes and their percentage of representation. This diverse scenario underlines Mato Grosso do Sul's creative and entrepreneurial capacity, besides indicating a robust commitment to innovation and sustainable development, an essential factor for regional and national economic growth.



<b>How many employees does your startup have?</b>		<b>The idea for creating your startup originated from:</b>	
No employees	57,1%	Academic/University Experience	25,0%
Between 1 and 3 employees	28,6%	Work experience	46,4%
Between 4 and 9 employees	14,3%	Both academic/university and work	28,6%
<b>How much do you agree with the statement: "Our startup has a clear strategy for future growth"?</b>		<b>How much do you agree with the statement: "We are ready to expand our business to other states"?</b>	
Strongly agree	0,0%	Strongly agree	32,1%
Agree	60,7%	Agree	17,9%
Neutral	14,9%	Neutral	21,4%
Disagree	21,4%	Disagree	14,3%
Strongly disagree	0,0%	Strongly disagree	1,3%
<b>Do you believe that partnering with universities, research institutions, or innovation support institutions has helped in the development of your solution?</b>		<b>Do you believe that the solution offered by your startup positively contributes to the reduction of environmental impacts?</b>	
Yes, completely	21,4%	Yes	60,7%
Yes, partially	35,7%	No	28,6%
Neutral	0,0%	I don't know	10,7%
No, they did not help	28,6%		
No, and they hindered development	14,3%		
<b>Do you believe your startup is well-positioned to attract investors?</b>		<b>What is the main innovation your startup has brought to the market?</b>	
Yes	32,1%	Innovative product/service	64,3%
Maybe	42,9%	Innovative business model	14,3%
No	25,0%	Innovative technology	21,4%
<b>What is the biggest challenge your startup is currently facing?</b>		<b>What are the main goals of your startup for the next 3 years?</b>	
Financial	21,4%	Geographic expansion	17,9%
Marketing	28,6%	Launching new products/services	28,6%
Product development	35,7%	Increasing revenue	17,9%
Team formation	0,0%	Attracting investments	25,0%
Others	14,3%	Others	10,7%

**Table 1:** Survey Conducted with the 28 Startups Monitored by Program

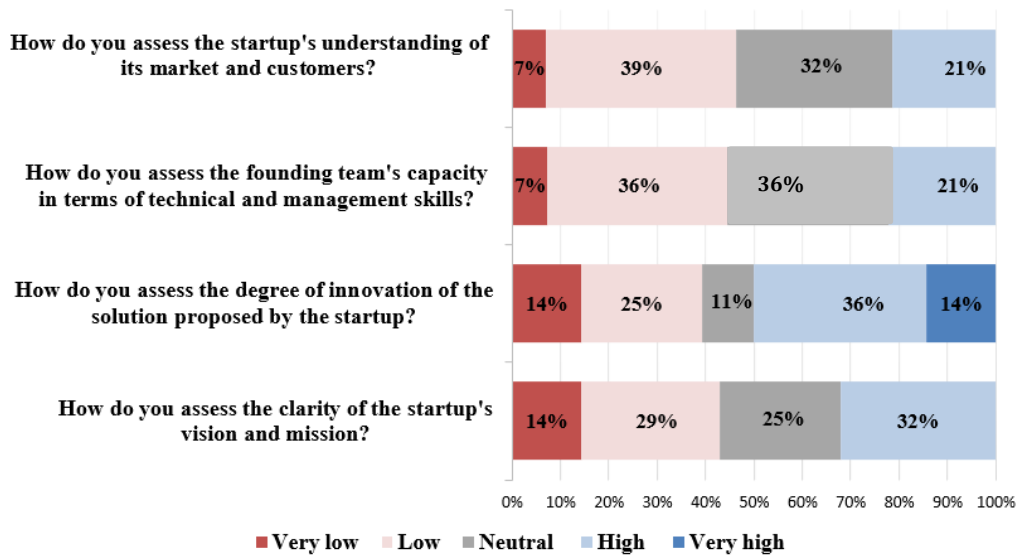
Concerning the origin of the idea for creating the startups, it is noteworthy that a significant portion originates from ideas that emerge from academic/university experiences (25%), highlighting how knowledge in entrepreneurship and innovation can assist these projects in reaching potential consolidation. Furthermore, the responses describe a very promising scenario regarding innovative solutions aligned with market trends, where the creation of innovative products/services emerges as the primary objective (64.3%), followed by innovative technologies (21.4%) and innovative business models (14.3%). In addition, 60.7% of startups believe that their solutions contribute positively to reducing environmental impacts, and the same percentage of entrepreneurs agree that their startups have a clear strategy for future growth.

In expansion terms, 32.1% believe they are ready to expand their businesses to other states, and the same percentage consider that their startups are well-positioned to attract investors. Despite this positivity, some points presented in the survey describe an inconsistency since the most significant challenges currently faced are product development (35.7%), followed by marketing (28.6%) and financial issues (21.4%).

One thing that stands out in this survey is that, although the program has the support of various institutions, 28.6% of the startup entrepreneurs believe that the partnerships with universities and innovation support institutions have not helped in the development of their solutions, and 14.3% say that these partnerships have even hindered development.

To better understand the percentages obtained in the survey and check whether the mentors share these same perceptions, a semi-structured survey was conducted with the 12 mentors of these startups. This second survey had ten questions, addressing both the solutions and the vision of the entrepreneurs to evaluate the consistency of the information obtained in the first survey.

In the survey conducted with the entrepreneurs, 60.7% said they had a solution that positively contributes to reducing environmental impacts. However, when mentors were asked, "Is the solution aligned with measures to reduce environmental impacts in the region?" the mentors pointed out that only 39.2% of the solutions were aligned with purposes contributing to reducing environmental impacts. The mentors were asked four questions to quantify their perceptions on specific points. Graph 2 describes their perceptions on these 4 points.



**Graph 2:** Mentors' Evaluation of the Sample of Technical and Management Skills

The results of the mentors' assessment reveal important and contrasting aspects concerning the vision passed on by the startup entrepreneurs. When assessing the clarity of the startups' vision and mission, 43% of the mentors classified the startups as having low or very low clarity. This might indicate that some startups need to improve the definition and communication of their vision and mission, besides reflecting a mismatch between the solution and the target audience, which impacts strategies to achieve validation and scalability.

Regarding the innovation degree of proposed solutions by these startups, 50% of the mentors rated innovation as high or very high. However, 39% see innovation as low or very low, indicating that a significant proportion of startups still face challenges in developing truly innovative solutions.

The founding team's technical and management skills capacity is also a critical area, with 43% of mentors rating it as low or very low. The profile of the entrepreneurs can explain this, as it is seen in Table 1 that 57.1% of the entrepreneurs have no employees. These entrepreneurs might even rate themselves capable of developing the proposed solution, but the team of mentors does not have the same confidence level. Continuous training in technical and management areas may be essential to overcome these challenges.

Regarding market understanding and customer insights, 46% of the mentors rated it as low or very low. It indicates that many startups need to significantly improve their knowledge of the market in which they operate and the needs of their customers. Only 21% of mentors consider that startups have

a good understanding of the market, which indicates a significant gap that must be addressed to ensure that the solutions offered are genuinely relevant and practical. Table 2 describes other points raised by the mentors.

<b>What is the main strength of the startup you are overseeing?</b>	
Technological Innovation	28,6%
Qualified Team	25,0%
Execution Capability	14,3%
Strategic Vision	14,3%
Others	17,9%
<b>What is the main area for improvement for the startup you are overseeing?</b>	
Product Development	53,6%
Strategic Partnerships	21,4%
Organizational Structure	14,3%
Marketing and Sales	10,7%
<b>Do you believe the startup has potential to attract investments?</b>	
Yes, with significant improvements	64,3%
No	25,0%
Yes, with some improvements	7,1%
I don't see potencial	3,6%
<b>What are the biggest challenges the startup is currently facing?</b>	
Customer Acquisition	35,7%
Qualified Personnel for Work/Partnership	7,1%
Scalability	3,6%
Financing	3,6%
Compliance/Regulation	3,6%
Others	46,4%
<b>What recommendations would you give to help the startup mature and grow?</b>	
Investing in Product Development	42,9%
Expand Strategic Partnerships	28,6%
Increase Focus on Marketing and Sales	10,7%
Seek More Investment	7,1%
Strengthen the Team With Technical Expertise	7,1%
Others	3,6%

**Table 2:** Survey Directed to the 12 Startup Mentors

As can be seen, the mentors identified technological innovation as the startup's main strength, followed by a qualified team. This indicates that the startups are bringing advanced solutions and have competent teams. However, product development is highlighted as the main area for improvement, suggesting a need for substantial adjustments and modifications so that the startups become more attractive to investors. In addition, strategic partnerships and organisational structure are other areas that need attention.

Regarding the potential to attract investment, the mentors believe that 64.3% of the startups can attract investment with the intention of "betting" on the solution presented and helping to insert it into the market, but that, to do so, the startups must make some improvements to their products/services, reflecting a need for substantial adjustments and modifications so that the startups become more attractive to investors. In addition, the mentors identify that 25% of the startups they accompany do not have the potential to attract investors.

The significant figure of 25% of the startups tracked not having the potential to attract investors can be explained in response to the challenges they currently face, which include customer acquisition (35.7%), which is in line with the need to improve marketing and sales. In addition, the "Other" category suggests a variety of unspecified but relevant challenges. This diversity of challenges indicates that startups face multiple and varied obstacles that require customised approaches.

To help startups mature and grow, mentors recommend investing in product development (42.9%), reinforcing the main area for improvement identified. Expanding strategic partnerships and increasing the focus on marketing and sales are crucial steps for growth. These recommendations reflect the need to strengthen startups' internal foundations and increase their capacity for market penetration.

## 5. Conclusions

This study analysed the challenges faced by startups participating in the Centelha II Program in Mato Grosso do Sul, focusing on their sustainable innovation practices and the main obstacles encountered. Using a field research approach, data was collected through semi-structured interviews with entrepreneurs and structured questionnaires with mentors, providing a comprehensive view of the perceptions of both groups.

One of the main disparities noted in the comparison between the two groups is that while 60.7% of entrepreneurs describe their solutions as positive for reducing environmental impacts, mentors believe that only 39.2% are aligned with solutions that can help reduce environmental impacts. This might be how entrepreneurs see their solutions but still struggle to externalise these benefits convincingly.

Another significant contrast is that while more than half of the entrepreneurs believe they have a clear strategy for future growth and are ready for territorial expansion, mentors assess that 68% of the startups have low clarity in their mission and vision. This mismatch suggests that few entrepreneurs need to better define and communicate their vision and mission.

Although 64.3% of the entrepreneurs believe they have a product/service solution ready for the market, the mentors strongly disagree with this view. Only 50% of the startups were classified by the mentors as having a solution with a high or very high degree of innovation, and 53.6% needed to improve their product development. In addition, the startup' entrepreneurs aim to launch new products/services and attract investors. Still, the mentors assess that only 21% of the startups understand the market and the customers they are trying to serve.

The mentors' recommendations emphasise the importance of investing in product development, expanding strategic partnerships, and increasing the focus on marketing and sales. These actions are essential for strengthening startups' internal foundations and improving their ability to penetrate the market. However, the negative perception of some entrepreneurs about partnerships with universities and research/innovation institutions points to the need to rethink and improve these collaborations to be genuinely beneficial.

To gain a deeper understanding of the challenges and opportunities facing startups in Mato Grosso do Sul's innovation ecosystem, it is recommended that future studies be carried out with a more extensive and diverse sample. Expanding the survey to include a more significant number of startups and mentors could provide a more representative and detailed view of the needs and potential of this sector. In addition, studies with follow-up time throughout the entire journey, from the ideation phase of these startups, would be valuable for identifying trends and evaluating the impact of specific interventions, such as mentoring programs still within universities.

Investigating the causes of the discrepancy between the perception of entrepreneurs and mentors is also crucial to developing adequate support and training strategies, ensuring that startups are better prepared to face challenges and take advantage of market opportunities.

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# A systematic review and bibliometric analysis of life cycle assessment in public procurement

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## Abstract

This study aims to demonstrate how public procurement can contribute to sustainable development and climate change through the use of the life cycle assessment (LCA) method. A systematic literature review was conducted using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method, combined with a bibliometric analysis of life cycle assessment (LCA) in public procurement. The bibliometric analysis was supported by the Bibliometrix software. This analysis concluded that the selected studies present barriers to the implementation of LCA in public procurement. Namely, it was verified that the application of LCA in public procurement encountered the most difficulties related to the existent guidelines, mainly related to the complexity of the processes and the lack of knowledge and awareness associated with the uncertainty and standards regulations. For future research, and considering the main barriers identified, it would be important to evaluate the creation of a tool based on LCA that facilitates the application of regulations aimed at sustainable development. This would enable public buyers to clearly apply the sustainability criteria in public procurement as stipulated by law. Additionally, since the barriers identified in this study were related to developed countries, it would be essential to identify barriers within the context of developing countries for effective implementation.

Keywords: life cycle assessment (LCA); sustainable public procurement; systematic literature review; barriers.

## 1. Introduction

The concern with reducing carbon emissions has become increasingly evident as the impacts of climate change become more severe and frequent. To drive actions in this direction, various international legislations and policies have been developed, such as the United Nations Framework Convention on Climate Change (1992), the Kyoto Protocol (2005), the Sustainable Development Goals (UN, 2015), and the Single Market for Green Products Initiative (EC, 2013) (Welling & Ryding, 2021). Thus, countries have set targets according to their capacities and specific circumstances to limit global warming, which involves substantially reducing emissions by 2030 and achieving climate neutrality by 2050. According to the Paris Agreement (2015), Brazil's target for 2025 is to reduce emissions by 37% compared to 2005 levels and by 43% by 2030.

In this context, countries are focused on developing national strategies that contribute to the global goal of mitigating climate change across all sectors of the economy. This includes public procurement, which has a significant impact on GDP, representing, for example, 14% in Europe (Orfanidou et al., 2023) and 12% in Brazil, as reported by the Organization for Economic Cooperation and Development (OECD, 2020). Hence, Green Public Procurement (GPP) emerges, as defined by the EU, as a procurement process with reduced environmental impact throughout its life cycle when compared to the same goods, services, and works acquired otherwise (EU COMMISSION, 2008). According to (Orfanidou et al., 2023), these processes, in line with the European Green Deal Investment Plan (COM, 2020), will be subject to additional legislation with mandatory minimum green criteria or targets for public procurement. It is important to mention that the term GPP has evolved into Sustainable Public Procurement (SPP) introducing social criteria in bidding decisions (Fregonara et al., 2022), opening the way for a more holistic and sustainable analysis in public procurement.

The adoption of environmental criteria in public procurement is commendable, but it becomes subjective when applied during the development of procurement procedures. For this reason, European guidelines encourage public service buyers to use methodologies such as Life Cycle Costing (LCC) in green procurement of goods and services, as well as other existing tools that address financial, environmental, and social issues, such as Life Cycle Assessment (LCA) (Orfanidou et al., 2023). LCA is considered by the European Commission and international literature as the best available framework for measuring and interpreting the environmental impacts of all activities, products, and services (UNEP/SETAC, 2015). Therefore, interest in its application has recently increased (Welling & Ryding, 2021).

Despite the growing interest in green procurement, the application of environmental criteria by public buyers in the procurement of goods and services is not yet mandatory. This gap between policy and practice is particularly evident in Brazil, where the Law 14.133/2021 mentions the need to consider environmental criteria in procurement processes, as yet to be enforced by regulatory bodies. Empirical evidence reveals that buyers face difficulties in operationalizing these guidelines, as the results of these tools can be difficult to understand for those with less experience in the field. This highlights the need for tools that can facilitate interpretation and guidance in this process, making the application of environmental criteria more accessible and practical for all public buyers.

In this regard, barriers are encountered in the application of sustainable public procurement, which may hinder the implementation of LCA. These barriers can be financial, such as the high cost of green products; legal, such as the lack of government legislation; personal, such as cultural resistance; educational, such as the guidelines issues and the lack of knowledge and awareness; and organizational, such as GPP policies and strategies, lack of incentives, and lack of political and top management commitment (Vejaratnam et al., 2020).

This article aims to understand the potential role played by LCA in public procurement and its contribution to sustainable public procurement. The article also identifies the current barriers to implementing LCA in sustainable public procurement. The following section (Section 2) provides an overview of the method used. Section 3 describes the main results found. Section 4 presents the discussions about the results, and Section 5 is a brief conclusion.

## 2. Methodology

To comprehensively understand the scientific production on Life Cycle Assessment (LCA) in Public Procurement, a methodology was employed combining a systematic literature review and a bibliometric analysis. The chosen approach considered the integration of these methodologies, which can effectively demonstrate the evolution of scientific studies quantitatively through bibliometric analysis, as well as in a qualitative manner through an in-depth exploration of topics and contents via systematic review

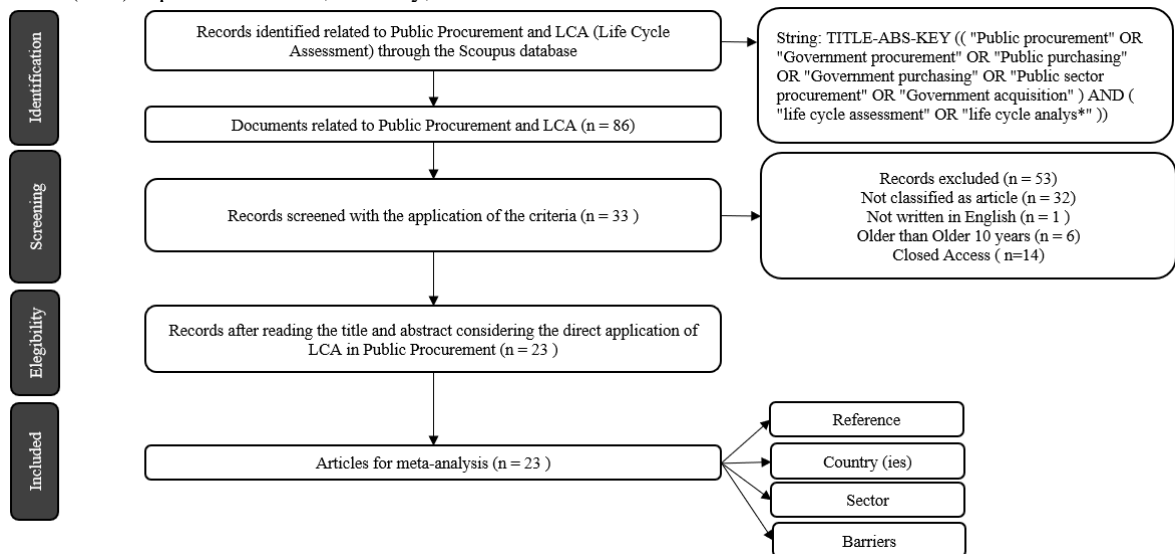
using the PRISMA method (Preferred Reporting Items for Systematic Reviews and Meta-Analyses). Notably, the PRISMA method consists of four phases (Identification, Screening, Eligibility, and Inclusion), as presented in Figure 1. For the bibliometric analysis, the Bibliometrix software was used. This open-access program creates and visualizes bibliometric maps, simplifying result interpretation. Its user-friendly interface and features enable efficient data examination, providing researchers with valuable insights (Boloy et al., 2021).

In the first phase of the PRISMA Method (Identification), the search strategy and terms were defined using the advanced mode, considering previous expert comments and the knowledge of the research unit, externalized in the Scopus database through the search string: TITLE-ABS-KEY (("Public procurement" OR "Government procurement" OR "Public purchasing" OR "Government purchasing" OR "Public sector procurement" OR "Government acquisition") AND ("life cycle assessment" OR "life cycle analys\*")). The Scopus database was chosen due to its consistency, standardization, and credibility. Additionally, Scopus is considered one of the most comprehensive databases in this specific area (Boloy et al., 2021) and has presented a significant number of published works on this topic.

In the Screening phase, records from the Scopus database published in the last ten years were selected, considering English-language articles from indexed journals. Of the 86 documents screened from the Scopus database, 33 were selected after discarding 53 due to the refinement criteria in the screening phase (period between 2014 and 2024 – until July - and classified as English-language articles). The studies from the last 10 years were selected due to the significant increase in publications during this period. At this point in the discussion, the results included 33 documents.

The Eligibility phase selects the articles to be considered in the study. The titles and abstracts of the thirty-three articles selected in the previous step were read, and those that did not present practical application of the LCA method in Public Procurement were removed. Thus, 23 articles were considered in the subsequent meta-analysis developed by the authors.

In the Inclusion phase, the authors conducted a full reading of the selected documents and analyzed them in detail. Information about the twenty-three documents was organized to show the literature found specifically on cases of LCA application in Public Procurement. The information was divided into 4 (four) topics: Reference, Country, Sector and Barriers.



**Figure 1:** Systematic Review using the PRISMA method.

### 3. Main Results

#### 3.1. Bibliometric Analysis

Analyzing the publications on LCA and Public Procurement chronologically, it can be observed from Figure 2 that the average number of publications has increased over the years, with two noticeable jumps: in 2015 and 2019. The years with the most publications are 2019 and 2023, both with 11 documents.

It is noted that publications began in 2005, which can be explained by the occurrence of various events encouraging immediate actions to protect natural and environmental resources and reduce GHG emissions (Li et al., 2021). The Kyoto Protocol, ratified by 192 countries, came into effect in 2005, and the identified jumps, as well as the number of publications may have been influenced by events occurring from 2015 onwards, such as the adoption of the 17 Sustainable Development Goals in September 2015 and the Paris Climate Change Conference in the same year. Additionally, the annual Conferences of the Parties of the United Nations Framework Convention on Climate Change (UNFCCC) can also influence these numbers. In 2025, the conference will be held in the city of Belém, PA, Brazil.

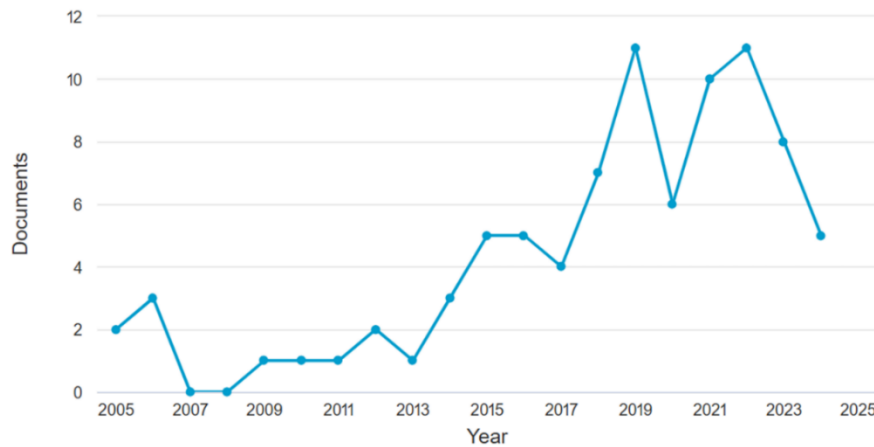
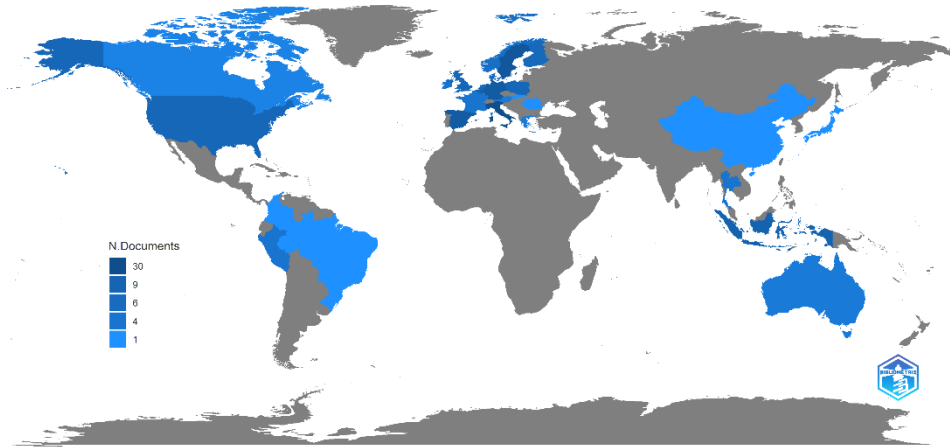


Figure 2: Documents by year

Regarding scientific production by country, Figure 3 shows that Italy, Sweden, and Germany were the leading producers of work on the analyzed topic over the past ten years, with 30, 18, and 15 articles published, respectively. It is important to note that the number of publications also considers collaborations, which is why the sum of publications does not match the total number of analyzed articles.



**Figure 3:** Country Scientific Production (produced using the Bibliometrix Software)

The number of publications related to the studied topic in the highlighted countries can be explained by the official commitments made by various national governments worldwide, whether through legislation, proposed measures, or policy documents, to achieve net zero greenhouse gas (GHG) emissions (Welling & Ryding, 2021). These commitments require developing long-term strategies aimed at significantly reducing GHG emissions, aligned to limit the temperature increase to 1.5°C above pre-industrial levels by the year 2050 (Gonzales-Calienes et al., 2022).

Regarding the authors' keywords identified in the studies, they were analyzed according to their number of occurrences. The number of occurrences is presented in the WordCloud map, where it was possible to visualize the keywords with higher and lower occurrences, suggesting gaps and trends in the literature. The most used keyword by authors is "Life Cycle Assessment" with 50 occurrences, certainly, because it is the main term searched in the publications. For this reason, it was necessary to remove this keyword from the analysis so that the other keywords would be visible in Figure 4.



**Figure 4:** WordCloud Authors'keywords (produced using the Bibliometrix Software)

Of the 50 keywords used by the authors, the ten most cited are: "green public procurement" (21-29%); "environmental product declaration" (11-15%); "public procurement" (10-14%); "life cycle costing" (6-8%); "circular economy" (5-7%); "sustainability" (4-6%); "carbon footprint" (5-7%); "sustainable public procurement" (4-6%); "asphalt" (3-4%); and "circular public procurement" (3-4%).

The keywords "green public procurement," "environmental product declaration," "public procurement," "sustainability," and "carbon footprint" represent approximately 70% of the studies, as

they are well-established terms in the literature and have been widely used over the years. Economic analysis is also prominent, which justifies frequently using the keyword "life cycle costing." The terms "circular economy", "sustainable public procurement" and "circular public procurement" are newer concepts that have emerged, particularly in the last two years. The keyword "asphalt" appears in a considerable number of studies, reflecting the construction sector's significant use of the LCA method in its environmental analyses for public procurement.

### 3.2. Systematic Literature Review

Analyzing all the articles read, it is observed that the works are mainly from Europe (87%), specially from Italy (30%). Regarding the application sector, most work is applied to the Construction (47%), Food (26%), and Transportation (9%) sectors. The most frequently used journals for publishing these works were Sustainability (34%), International Journal of Life Cycle Assessment (26%), and Sustainable Production and Consumption (9%).

Considering the barriers identified in the study by (VEJARATNAM; MOHAMAD; CHENAYAH, 2020), the author conducted the same analysis, in order to identify these barriers but in the application of LCA in public procurement. The main barriers to the application of sustainable public procurement identified in the studies are related to "guidelines issues" and the "lack of knowledge and awareness", both at 39%. Other barriers were also identified, albeit in smaller numbers, such as 'lack of incentives,' 'lack of monitoring and evaluation,' all at 17%. The 'high cost of green products' barrier was identified in 13% of the studies.

No	Reference	Country	Sector	Finance		Legal			People			Knowledge			Organisation					
				L	H	R	L	A	L	L	S	G	L	D	P	O	P	M	L	
				B	C	L	L	L	C	E	I	I	K	P	S	S	T	E	I	
1	(PEREZ-NEIRA; SIMÓN; COPENA, 2021)	Spain	Food Sector						X						X					
2	(VÁZQUEZ-ROWE et al., 2021)	Peru	Construction										X					X		
3	(CERUTTI et al., 2016)	Italy	Food Sector									X	X							
4	(LINGEGÅRD; HAVENVID; ERIKSSON, 2021)	Sweden	Construction							X										X
5	(WELLING; RYDING, 2021a)	Sweden	Food Sector/Construction							X	X									
6	(DE LAURENTIIS et al., 2019)	U.K	Food Sector		X														X	
7	(MORETTI; DI MASCIIO; D'ANDREA, 2013)	Italy	Construction								X									
8	(BARBINI et al., 2020)	Italy	Construction																X	
9	(ORFANIDOU et al., 2023; TROVATO; NOCERA; GIUFFRIDA, 2020)	Italy	Construction																X	X
10	(ORFANIDOU et al., 2023)	Greece	General		X						X									
11	(WITCZAK et al., 2014)	Poland	General					X				X			X					X
12	(CERUTTI et al., 2018)	Italy	Food Sector										X		X					
13	(BIBIRE; CHITIMUS; GHENADI, 2023)	Romania	Transport		X								X							
14	(SENSENEY et al., 2023)	USA	Construction									X	X							
15	(KUITTINEN; HÄKKINEN, 2020)	Finland	Construction										X							
16	(KLINT; PETERS, 2021)	Sweden	General								X									
17	(KRETSCHMER et al., 2021)	Germany	Food Sector							X					X					
18	(FREGONARA; FERRANDO; TULLIANI, 2022)	Italy	Construction								X									
19	(PARCHOMENKO et al., 2023)	Belgium	General	X			X													X
20	(DIERKS et al., 2024)	Germany	Construction										X							
21	(FIORENTINO et al., 2024)	Italy	Transport									X								
22	(SCHERZ; KREINER; PASSER, 2023)	Austria	Construction									X	X							
23	(ZIJP et al., 2022)	Netherlands	General															X	X	
				1	3		1		2	2	1	9	9		3	1	2	4		4
	<b>Finance</b>	<b>Legal</b>	<b>People</b>	<b>Knowledge</b>																
	LB = Limited Budget	RL = Regulatory loopholes	LC = Lack of cultural change	GI = Guidelines issues										LK = Lack of knowledge and awareness						
	HC = High cost of green products	LL = Lack of government legislation	LE = Lack of expertise																	
		AL = Ambiguity in legal requirement	SI = supplier issues																	
	<b>Organisation</b>																			
	DP = decentralization of procurement	OS = organization size	ME = Lack of monitoring and evaluation																	
	PS = GGP policy and strategy	PT = Political and top management commitment	LI = Lack of incentive																	

**Table 1:** Systematic literature review

## 4. Discussion

As observed, the public procurement can be an important strategic policy instrument for promoting sustainable development (Luiz et al., 2024). Especially when it is observed that the conferences held around the world, such as the ones mentioned, contribute to the increase in studies on the topic of public procurement. This explains the reason that this increase is mainly observed in developed countries and, particularly, in Europe. And also, because the European Commission, through various actions, decisions, and interventions, has encouraged public authorities to make procurement decisions greener (Orfanidou et al., 2023). The study indicated that the application of Life Cycle Assessment (LCA) in public procurement can be one of the actions that assist in greening these purchases. This has been observed in several studies conducted in European countries such as Italy, Sweden, and Germany, which can be seen as references in this field. However, few studies were found in developing countries, indicating that there is much work to be done.

It was identified that the construction and food sectors are well-represented in terms of applying the LCA method in green public procurement. These sectors primarily focus on assessing environmental and economic impacts, using the LCC method in their approaches (Fregonara et al., 2022). It was also observed that these sectors extensively use LCA for creating Environmental Product Declarations (EPDs) (Gulotta et al., 2018; Senseney et al., 2023; Welling & Ryding, 2021) as a means to standardize the communication of environmental impacts throughout the product's life cycle. However, solely environmental and economic analysis is insufficient. A more holistic view of the process is important, which can be achieved through sustainable public procurement and circular public procurement (Lingegård et al., 2021), areas that have emerged in studies predominantly in the last two years.

This study further identified that applying the LCA methodology in public procurement can encounter numerous barriers, as observed in sustainable public procurement (Vejaratnam et al., 2020). From the systematic literature review, it was possible to identify the main barriers to applying LCA in public procurement. It was identified that the two primary current barriers presented in the studies were guideline issues and lack of knowledge and awareness. The studies indicated that the guideline issues barrier is mainly related to the complexity of applying LCA in the processes (Welling & Ryding, 2021). Regarding the lack of knowledge and awareness barrier, it was observed that while laws exist, they are not sufficiently clear, there are no standards, or they present some failure in the application of sustainability criteria (Cerutti et al., 2016; Kuittinen & Häkkinen, 2020; Senseney et al., 2023). It is important to note that most of the studies analyzed originate from developed countries. A different analysis is needed for developing countries due to their unique challenges and circumstances, as presented in the study by (Vázquez-Rowe et al., 2021) that noted that the application of LCA in public procurement can encounter not only technical and social issues but also transparency challenges. It is important to emphasize that for future studies, it would be crucial to conduct a more detailed and in-depth analysis of these barriers.

## 5. Conclusion

For the purpose of assessing the progress of studies involving Life Cycle Assessment (LCA) and public procurement, the authors considered the 86 documents found after applying the search string. The data were processed using Bibliometrix to enable bibliometric analysis. Through bibliometric analysis, the articles were examined considering publications by country and the co-occurrence of the authors' keywords. Most of the work on this topic has been developed in Europe, with Italy standing out for its numerous studies on LCA applied to public procurement in the construction sector. Regarding

the co-occurrence data of the authors' keywords, the result showed that the most used keyword is "green public procurement" precisely because it is a well-established topic in the literature. However, it was noticed the need for a more holistic view of the process has led to the emergence of topics, especially in the last two years, such as "sustainable public procurement" and "circular public procurement," thus addressing not only environmental and economic criteria but also social aspects.

After a bibliometric analysis, the authors performed a systematic literature review through PRISMA, showing the relationship between LCA and sustainable public procurement. A total of 23 papers were selected and categorized into four fields: Reference, Countries, Sector and Barriers. This analysis allowed to conclude that the studies present barriers to the implementation of LCA in public procurement. Thus, based on the barriers identified in sustainable public procurement, it was able to verify that for the application of LCA in public procurement, the studies encountered the most difficulties with guidelines issues, mainly related to the complexity of the processes, and lack of knowledge and awareness, related to the lack of clarity and standards in the law.

Thus, this study reveals the need to implement tools or models within purchasing processes, allowing users to integrate environmental criteria into their acquisitions. However, it was also found that there are barriers to this implementation, particularly related to the lack of knowledge and environmental awareness, which need to be overcome.

For future research, and considering the main barriers identified in the studies, it would be important to evaluate the creation of a tool based on LCA that facilitates the application of laws aimed at sustainable development. This would enable public buyers to clearly apply the sustainability criteria in public procurement as stipulated by law. Additionally, since the barriers identified in this study were related to developed countries, it would be essential to identify barriers within the context of developing countries for effective implementation.

**Funding:** Grant Number: 200.166/2023 Carlos Chagas Filho Foundation for Research Support in the State of Rio de Janeiro (FAPERJ) Grant Number: 306976/2021-8, National Council for Scientific and Technological Development (CNPq).

**This study was financed in part by the** Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - **Finance Code 001.**

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# Utilization of Excess Energy in Photovoltaic Plants Caused by Clipping: Efficiency Comparison between Battery and Green Hydrogen Storage Solutions

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## Abstract

When a photovoltaic plant project is sized, the system can be oversized to achieve greater utilization of the generation curve. However, during peak production times on days with higher irradiance, the generation curve may be cut (clipping), resulting in unused excess energy. This unused energy can be a challenge, especially for energy trading plants, as they are limited in injecting this energy into the grid at the same time as production. This study proposes turning this challenge into an opportunity by suggesting energy storage for later injection into the grid. For this, a comparison of efficiency between battery storage and green hydrogen storage solutions is performed. The analysis considers the same initial conditions for both storage options, along with the respective estimated losses for each process. The objective of this work is to compare the energy utilization profile over a 25-year lifespan of a photovoltaic plant for the two storage systems analyzed, considering scenarios with and without replacement of storage systems. The results of this study, which only compares the energy efficiency ratio, highlight a greater stored energy for the battery system and a trend with more attenuated variations for the green hydrogen system.

## 1. Introduction

In photovoltaic plant projects, it is possible to perform an overdimensioning, adding a peak installed power of DC (Continuous Current) photovoltaic modules higher than the rated power AC (Alternating Current) of the inverter. Thus, in moments of low irradiance, the additional photovoltaic modules will minimize this impact by maximizing the total energy produced. However, in moments of high irradiance, as the inverters are not able to transform all DC energy into AC due to the limitation of the nominal installed power, this energy is lost. This phenomenon can be called clipping, since there is a cut in the generation curve.

To circumvent this issue, the agent generators and traders of photovoltaic solar energy seek market solutions to utilize the generated excess energy. One of the most sought-after solutions is energy storage, for later injection into the grid during low irradiance periods. Conventionally, batteries are used. However, there are other storage methods, such as hydrogen. Specifically green hydrogen, which

is produced by electrolysis of water, through a renewable source in continuous current. In this sense, hydrogen becomes an option for analysis of the charging and discharging process in its production and transformation chain up to storage, because it presents characteristics applicable to photovoltaic plants.

Therefore, the objective of this work is to compare, over 25 years of useful life of a photovoltaic plant, the efficiency of battery storage systems with the green hydrogen storage systems, as contour solution options to avoid losses of excess energy caused by clipping.

## 2. Characteristics of storage systems

Based on the two solutions presented, it is possible to compare some main characteristics to analyze their performance. Table 1 demonstrates these characteristics for the battery or hydrogen storage options. Three items from this table can be highlighted for further development: Energy Density, Useful Lifetime/Lifespan, and Technical Maturity (TRL -Technology Readiness Level).

Energy density demonstrates the amount of energy that can be stored in a given volume. The higher this value, the more energy can be stored, and it is possible to supply power to a load for longer, before needing to be recharged again. Hydrogen has this aspect as an advantage over batteries.

The Lifespan corresponds to the period of use in service of an asset, while generating economic benefits. In this analysis, the lifespan of the green hydrogen storage system is generally longer. However, the time indicated for complete replacement of both systems must be considered so as not to compromise quality operation.

The Technical or Technological Maturity Level (TRL) is an important factor for analysis. because it defines at what stage the technology is in the level of progress of research and development activity. It is worth mentioning that this factor is mutable according to the analysis period. Between these two storage systems, the TRL of the battery is higher than that of green hydrogen.

Attribute	Battery	Hydrogen	References
Response Time	ms	min	(Assia Chadly, 2022)
Storage Time	Minutes/Days	Hours/Weeks	(Botteon, 2020)
Storage Capacity	kWh-MWh	MWh-GWh	(Fonseca, 2022)
Energy Density	1-100 Wh/kg	100-1000 Wh/kg	(Javier Tobajas, 2022) (Mukrimin Sevket Guneya, 2017)
Lifespan	Varies from 5-20 years	Varies from 20-40 years	(Boucar Diouf, 2015) (Hui Liu, 2012)
Efficiency	Varies from 85–98%	Varies from 50–60%	(Assia Chadly, 2022) (Farrancha, 2019)
Technical Maturity	More mature technology	Less mature technology	(Lucas Macedo da Silva, 2022)

Maintenance	System replacement when requested	Reduces the frequency of equipment replacements	(Esteves, 2017)
Toxicity and Environmental Risk	Harmful to the environment	Low greenhouse gas emissions	(Lucas Macedo da Silva, 2022)
Estimated Investment Cost	450 €/kWh	2800 €/kWh	(Barbosa, 2019)

**Table 1:** Battery and Hydrogen Storage Attributes

### 3. Methodology

The methodology of this work follows the steps below to use the same conditions of a designed plant to compare the energy efficiency between battery and green hydrogen storage methods.

#### 3.1. Sizing of the photovoltaic plant and initial energy for storage

In order to obtain a better measurement of results, average sizing values for installed power and clipping in photovoltaic plants were chosen. For installed power in Wp (Watt peak), the value of 300 MWp was chosen for use in this study, based on the most recent powers of plants installed around the world (Brasil Energia, 2017) (Canal Solar, 2021) (Canal Solar, 2024). For clipping, an average ratio of 1.3 between DC power and AC power was chosen (Leonardo Micheli, 2024). Based on these premises, the example plant in question would result in a maximum power transformed by the inverters of approximately 230 MW.

For that, an ideal clipping of 30% is estimated. This value of energy not used based on the ideal conditions of the plant will not be the stored value, need to pass through discounts for estimated losses. These losses can be divided between losses from climatic conditions and operational conditions to characterize a profile more consistent with reality. Losses due to climatic conditions reflect the meteorological variation that the location where the photovoltaic plant is installed may suffer. Losses due to operational conditions represent any interference with photovoltaic plant equipment and preventive or corrective maintenance routines.

To estimate the acceptable average loss value, we used the acceptable average value of 75% of Performance Ratio – PR (Gabriel Bastos Plantickow, 2021). The PR demonstrates the performance of the photovoltaic plant through the ratio of generated energy and optimal energy based on installed power and variations in climatic conditions. Therefore, with this reference value, the total losses of climatic and operational conditions result in an average of 25%. In this scenario, when there is clipping, considering the discount of losses, it is estimated that only 5% of the installed power can be stored. For this case study, resulting in an average unutilized power value of 15 MW. Considering 6 Peak Sun Hour (PSH) per day (Samira, 2021), it returns an average unused energy per day of 90 MWh for storage.

With the purpose of evaluate the annual performance of each storage system, 90 days of possible clipping were considered per year, in order to contemplate at least the summer season, which allows greater solar irradiance (Silva, 2022).

## 3.2. Battery Storage

For the battery option, lithium-ion batteries were chosen for presenting higher energy density, greater efficiency and longer life cycle, compared to lead acid batteries and other technologies (Bárbara A. L. Paixão, 2020). Currently, a viable option for photovoltaic plants is the BESS (Battery Energy Storage System). This system stands out for its advantages of balancing the electrical grid, providing backup energy during interruptions and improving the overall stability of the grid. However, this system was not dimensioned in this work; only technical characteristics of this type of battery were considered for the efficiency study.

For the battery storage option, the following losses were considered: Round-trip efficiency and Self-discharge rate.

The first factor considered reflects the round-trip efficiency, charge and discharge, of the battery system, which is represented by a curve provided by the manufacturer in line with the operating rate (C rate) of the battery system or by an efficiency percentage. The C rate represents the charge and discharge rate of an energy storage element relative to its maximum capacity. In a battery with a capacity of 30 Ah, if for a rate 1 C there is full discharge in 1h, for a rate 2 C, it is faster, the battery will discharge in half an hour its entire capacity, for example. For this efficiency, the value of 90% was considered (Canadian Solar, 2021).

The second factor considered is the rate of self-discharge, the batteries are self-discharge gradually even without being in operation and without existing current. This is due to chemical reactions that happen inside the cell, even in inertia. Lithium-ion batteries have self-discharge rate less than 5% per month (Maria de Fátima Negreli Campos Rosolem, 2020).

The round-trip efficiency was applied to the initial daily energy to be stored of 90 MWh, resulting in a final energy, after charging and discharging by the battery storage system, of 81 MWh per day.

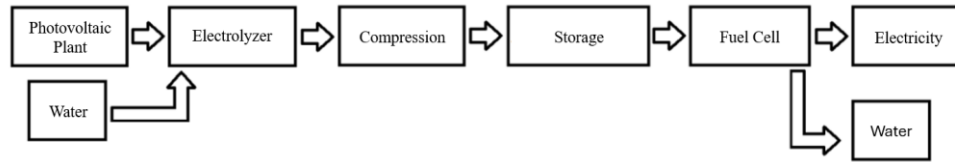
Considering the gradual self-discharge and changes in efficiency by temperature, it was considered an annual efficiency of 95% in the first year of operation, 97% per year until the twentieth year of operation (which represents the final year of useful life indicated by the manufacturer) and 94% per year until the twenty-fifth year, considering the round-trip efficiency drop (Canadian Solar, 2021).

For the analysis of the results, two scenarios were considered. The first scenario does not consider replacement of the storage system to replace batteries completely. Thus, it is possible to analyze the efficiency until the twenty-fifth year of operation of the plant, end of the useful life of the photovoltaic system, without interference (Brito, 2020). And the second scenario considering only one replacement to replace all equipment, in the thirteenth year of operation of the plant, depicting possible maintenance decisions. In this last scenario, the efficiencies are considered as the start of operation of the system.

## 3.3. Green Hydrogen Storage

For hydrogen storage option, the production of green hydrogen through local electrolyzer in the photovoltaic plant was chosen. This choice was made by producing from a renewable source, in the same production site, avoiding transportation costs and storage space is not a very big impact in this case.

As for the return of the final energy, the coupling of a fuel cell was chosen after the compression and storage of the hydrogen produced by the electrolyzer. This scheme can be better explained through the image below (Veiga, 2022).



**Figure 1:** Charging and discharging scheme of energy stored by green hydrogen

This option will be divided into charging (electrolyzer), storage (gaseous hydrogen) and discharge (fuel cell).

For the moment of charge was used an electrolyser model PEM (Proton Exchange Membrane). The electrolyser is a device that allows hydrogen to be produced by means of a chemical process (electrolysis). Water electrolysis is the chemical decomposition of water ( $H_2O$ ) into oxygen ( $O_2$ ) and hydrogen ( $H_2$ ) by the effect of an electric current passing through the water. This model stands out for coupling to photovoltaic plants due to its ability to respond quickly to power fluctuations. The PEM type electrolyser can operate under variable energy regime.

This is one of the differences when compared with alkaline electrolysers, because the transport of ions in this model presents a greater inertia. A factor of 80% was considered as the efficiency of the PEM electrolyzer, a higher efficiency when compared to the AWE (Alkaline Electrolysers) and SOE (Solid Oxide Electrolysers) models, for example (Seddiq Sebbahi, 2022).

Therefore, considering the initial energy at 90 MWh/day or 15 MWh, applying the efficiency of the PEM electrolyzer, the result is 12 MWh. Converting this energy to hydrogen quantity (Nm<sup>3</sup>/h), through 4.5 (kWh/Nm<sup>3</sup>) for this electrolyser (Seddiq Sebbahi, 2022), 2667 Nm<sup>3</sup>/h or 240 kg/h of hydrogen is generated.

From this generation capacity, it was considered a PEM electrolyzer with capacity of 4000 (Nm<sup>3</sup>/h) (Thyssenkrupp Nucera, 2022). Compared to other dimensions, this one has an ideal operating range of 400 (10%) to 4000 (100%), contemplating a good range of power oscillations.

Two options were raised for storage: liquid hydrogen and gaseous hydrogen. Since the gaseous hydrogen method has lower losses, this was chosen, since in the process of liquid hydrogen there would be losses by evaporation (Monteiro, 2023). To reflect this scenario, a minimum loss of 2% was estimated, applied to the volume of hydrogen before entering the fuel cell. Thus, the hydrogen volume found at 240 kg/h at the end of the load becomes 235 kg/h at the beginning of the discharge.

For the discharge moment, the PEMFC (Proton Exchange Membrane Fuel Cell) was considered. This Proton Exchange Membrane fuel cell transforms the chemical energy, released during the electrochemical reaction of hydrogen and oxygen, into electrical energy. This model stands out for its higher power density compared to the others (Farrancha, 2019).

For the fuel cell, an efficiency of 55% and a power density of 4.5 kW/m<sup>3</sup> were estimated (Farrancha, 2019). From this, a calorific value of 4.5 kWh/Nm<sup>3</sup> was considered, that is, 50 kWh/kg. Using this calorific value in the hydrogen volume of 235 kg/h, 11.7 MWh/h is obtained at the beginning of the discharge. Applying the considered efficiency of 55%, at the end of the discharge, 6.5 MWh/h is obtained, generating 38.8 MWh/day.

After all the transformations of the green hydrogen storage process, comparing the final energy of 38.8 MWh/day with the initial of 90 MWh/day, can be observed an overall efficiency of this process in 43%.

For the hydrogen cycle, considering the coupled system of electrolyzer, compression, storage and fuel cell, a degradation of 2.64% is estimated after 2 years of operation (Ender Ozden, 2017). From this, performing a linear forecast, an annual degradation of 1.32% is obtained. Therefore, the system presents 98.68% efficiency per year.

Similar to the battery storage system, for analysis and comparison of the results, the same two scenarios were demonstrated, one considering replacement of the equipment in 13 years of operation and the other not.

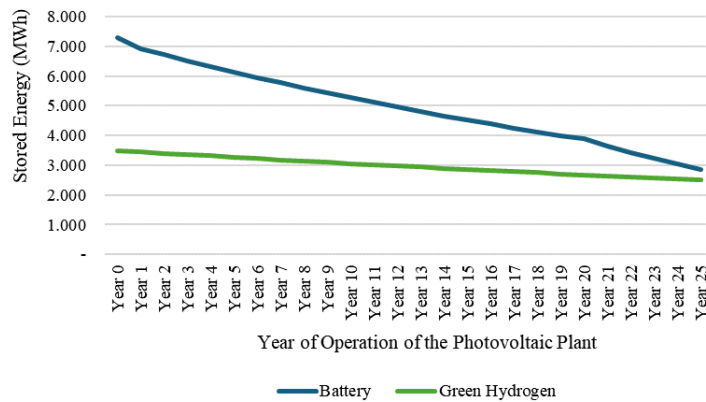
## 4. Results

The results of this study were based on the premises mentioned above, which can be summarized in Table 2.

Attribute	Battery	Green Hydrogen
Initial Energy Stored per Day (MWh)	90	90
Clipping Days per Year	90	90
Initial Energy Stored per Year (MWh)	8100	8100
Charge and Discharge Efficiency (%)	90%	43%
Annual Efficiency Year 1 (%)	95.00%	98.68%
Annual Efficiency Year 2 to 20 (%)	97.00%	98.68%
Annual Efficiency Year 21 to 25 (%)	94.00%	98.68%

**Table 2:** Assumptions Considered

From these defined and applied premises, two graphs were generated, presented in figures 2 and 3, respectively, to compare the storage profile of both options over 25 years. The first does not consider system replacements and the second considers complete replacement of the systems in the thirteenth year of operation.

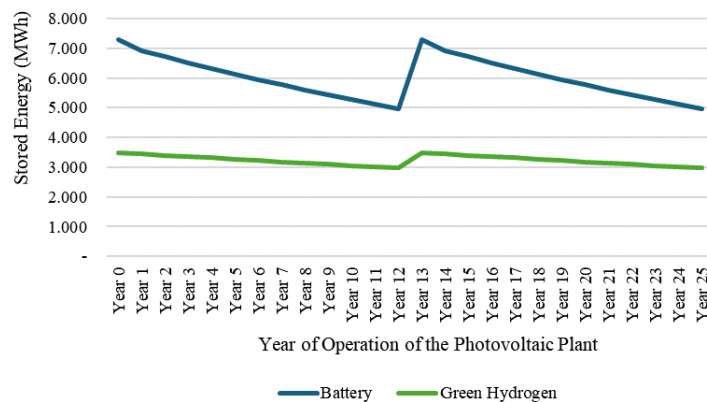


**Figure 2:** Comparison of results without system replacement

Analyzing the first scenario, it is observed that the initial energy of the green hydrogen storage system is approximately half of the initial energy of the battery storage system. This is a result of the low efficiency of the green hydrogen system compared to the battery system, after charging and discharging, 43% and 90%, respectively. The low efficiency of the green hydrogen system is a consequence of the number of transformations involved in the whole process and consequently higher losses until the energy to be discharged.

It is noticed that the self-discharge rate of the battery directly influences the energy curve of this system, showing a significant decrease in the value of stored energy over the years. Relating the year 25 to the year 0, the battery system has an efficiency of 39%, while the green hydrogen system has an efficiency of 72%.

Therefore, if there is no replacement of the system equipment, the final energy in year 25 is closer to the initial energy in year 0 in the green hydrogen storage system. But, because the initial energies are different and there is a higher initial energy for the battery system, this system has more stored energy in year 25. However, the value presented in both systems in year 25 is similar between them, even with the large initial difference. Presenting more similar energy values over the years and more approximate curves.



**Figure 3:** Comparison of results with system replacement

The objective of considering a second scenario with the replacement of the systems was to evaluate the change in the energy stored curve, considering that it is a probable maintenance action to be carried out over 25 years.

In this scenario, it can be observed that the increase in efficiency and consequent stored energy is greater for the battery system. The green hydrogen system, on the other hand, presents a more subtle efficiency gain. This factor can be decisive in an investment analysis with the objective of improving the efficiency of the system.

From year 13 onwards, with the performance of new equipment and efficiency similar to that of the year 0, energy curves are distancing. However, continuing to consider annual efficiency drops, the curves tend to approximate over the years.

In this scenario, relating the year 25 to the year 0, the battery storage system returns an efficiency of 68% and the green hydrogen storage system of 85%. Comparing this scenario with the scenario that does not consider replacements, the efficiency gain for the battery system is clear, from 39% to 68%. However, the green hydrogen storage system does not show such a significant gain, 72% to 85%.

The annual energy stored is higher in the battery storage system, in both scenarios, for all years. The efficiency drop at the end of 25 years is lower for the green hydrogen storage system in both scenarios.

Although this study considered some characteristics of a BESS system with lithium-ion batteries, which includes battery costs, plus the cost of the electronic control system and a longer useful life, considering a more conservative scenario and variations in other technologies present in the market, the average replacement times for the systems are 4 years for the battery and 15 years for hydrogen (Sergio Silva, 2010). For the hydrogen system, not all components need to be replaced in 25 years, such as the cylinders that reach the end of their useful life at the end of the photovoltaic plant's operation (Sergio Silva, 2010). However, in an analysis of total replacement of the two systems, it is observed that in 25

years, the battery system would be replaced 4 times and the hydrogen one time. However, in a total replacement analysis of the two systems, it is observed that in 25 years, the battery system would be replaced 4 times and the hydrogen one time. Considering the investment costs of both systems mentioned in Table 1, as initial investment and replacement cost, the total cost of the battery system would be 2250 €/kWh and hydrogen 5600 €/kWh. Therefore, the battery system becomes more advantageous than just the initial investment of the hydrogen system.

Table 3 highlights the main results of both systems.

Attribute	Battery	Green Hydrogen
Initial Energy Stored per Day (MWh)	90	90
Final Energy Stored per Day (MWh)	81.0	38.8
Daily Charge and Discharge Efficiency (%)	90%	43%
Initial Energy Stored in Year 0 (MWh)	7290	3492
Efficiency in 25 years without replacement (%)	39%	72%
Efficiency in 25 years with replacement (%)	68%	85%

**Table 3:** Results

## 5. Conclusion

The study concluded that, now, energy storage in batteries is more efficient than green hydrogen storage. This higher efficiency of batteries is due to the smaller number of transformations involved in the process, resulting in lower losses. Batteries stand out for solid technology and wide applicability, while green hydrogen offers advantages such as long-term storage, longer service life, and potential for exploration of by-products such as oxygen and hydrogen for sale.

The presented graphs suggest that if the green hydrogen storage system reaches a higher Technical Maturity Level (TRL) and the process of transformations generate less losses, it may be possible for the lines on the graphs to cross before year 25. This would result in a higher efficiency for this system, compared to the battery system, after a certain year of operation.

For a more complete energy and sustainable analysis, it is important to consider the auxiliary consumption of equipment and the use of water in the process of producing green hydrogen. Although the study focuses on efficiency, the future technical and financial analysis would be necessary to assess the return on investment and long-term viability of both storage options. Thus, the choice between batteries or green hydrogen will depend on specific objectives, installed capacity of the plan, surplus energy, technologies chosen, initial investments (CAPEX), operating expenses (OPEX) and the expected operating time of the system.

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# Metal phosphates electrocatalysts applied for hydrogen evolution reaction

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## Abstract

In Over the years of the increased demand for energy to meet the needs of humanity's technological advances, new clean energy sources have been sought to replace fossil fuels. In this work, nickel and cobalt phosphates-based electrodes on fluorine doped tin oxide (FTO) substrate were fabricated and analyzed to evaluate their application in the hydrogen evolution reaction. The metal phosphates were coated on FTO substrate through constant potential electrodeposition method. The nickel phosphate (NiP) electrode presented an overpotential of 169mV, showing a better response when compared to the cobalt based electrode. It is encouraging that the NiP electrodes will remain the focus of research to generate hydrogen electrochemically.

## 1. Introduction

The development of sustainable energy sources has received considerable attention from scientists around the world to reduce the burning of non-renewable and environmentally harmful fossil fuels. In this vein, the possibility of applying hydrogen as a replacement for fossil fuels has been targeted (Midilli & Dincer, 2008; Megía, Vizcaíno, Calles, & Carrero, 2021).

Hydrogen is the most abundant chemical element in the visible universe (Field, 1995). When compared to other energy sources, molecular H<sub>2</sub> has an advantage in energy density per mass, approximately 143 MJ.kg<sup>-1</sup>, against 46.4 MJ.kg<sup>-1</sup> for gasoline, 45.4 MJ.kg<sup>-1</sup> for diesel and MJ.kg<sup>-1</sup> for biodiesel (Mazloomi & Gomes, 2012).

Currently, most H<sub>2</sub> production is done through non-renewable sources that affect the environment, such as steam reforming of methane gas (Voldsund, Jordal, & Anantharaman, 2016; Sidorenko, Kutkina, Nazarova, & Brykin, 2022). Water electrolysis is considered an ecological and viable technique for producing hydrogen and is a process widely known and explored in the literature (Chi & Yu, 2018; Kumar & Lim, 2022). However, the oxygen evolution reaction (OER) at the anode is a slow and limiting process in the efficiency of water electrolysis. Noble metals and their oxides, which are expensive and scarce in the environment, are commonly applied to promote the molecular breakdown of water due to their high activity and stability, making their use economically unfeasible (Dong, et al., 2019; Huang, et al., 2019).

Global research groups have been tinkering away new forms of emission-free hydrogen generation energy sources (Pathak, Yadav, & Padmanaban, 2023; Qureshi, et al., 2023). One challenging feature of hydrogen production is that it is not naturally occurring in the environment, instead, it requires processes to separate the substances or molecules that contain it. The division of the water molecule into O<sub>2</sub> and H<sub>2</sub> does not occur spontaneously, and a certain amount of energy must be supplied to the system for this to occur. This indicates that electrochemical methods can be used to split water

molecules (Darband, Aliofkhaezrai, & Shanmugam, 2019; Raveendran, Chandran, & Dhanusuraman, 2023). For water separation, a Thermodynamic Equilibrium Potential (TEP) must be sufficient. In order for the slow rate of hydrogen evolution reaction (HER) to be enhanced, the system needs to be supplied with additional energy. Overpotential ( $\eta$ ) is the term used to describe this potential rise above the theoretical limit (Govind Rajan, Martirez, & Carter, 2020; Anantharaj, et al., 2018).

Electrocatalysts that possess high current density and low overpotential are critical for successful hydrogen evolution (Chen, et al., 2020; Xu, Wang, Huang, & Fu, 2021). Because of their characteristics, platinum and platinum-based materials have been widely applied to produce electrodes capable of deliver high current density at low overpotential for HER (Ma, et al., 2023; Li & Baek, 2019). The high cost and scarcity of Pt have encouraged scientists to develop new materials suitable for replacing it (You & Sun, 2018; Ibn Shamsah, 2021). In such a way, new materials have been proposed to replace the noble metals applied in the electrochemical hydrogen production, including metal alloys (Bai, et al., 2016), chalcogenides (Dastafkan & Zhao, 2020), carbides (Deng, et al., 2021), borides (Chen, et al., 2018) and nitrides (Yu, et al., 2019).

In this work, two metallic phosphates were fabricated by electrodeposition on FTO glass and investigated to analyze their performance in the hydrogen evolution reaction. In this way, aiming it to get a low-cost and abundant material with low overpotential and high catalytic activity for environmentally friendly hydrogen production, capable of replacing platinum-based electrodes in water electrolysis.

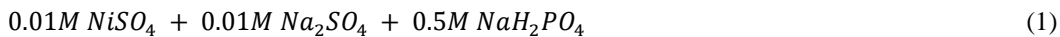
## 2. Materials and Methods

The substrates used to deposit the materials throughout the work are glass slides with a thin conductive layer of tin dioxide fluorine doped ( $\text{SnO}_2$ ), FTO - acronym for Fluorine Tin Oxide, with surface resistivity of  $10\Omega/\text{sq.}$ , purchased from Sigma Aldrich. The reagents used throughout the work were purchased from Brazilian company Exodus Cientifica. In this work all electrodes were fabricated from electrodeposition technique. Electrodeposition is a low-complexity electrochemical method for producing materials, but which provides surfaces with greater regularity and homogeneity, when compared to other simple deposition techniques such as drop casting.

The technique consists of applying a difference in electrical potential between two electrodes (anode and cathode) submerged in a precursor solution. The method is divided into two modalities: constant potential deposition (potentiostatic electrodeposition) or constant current (galvanostatic electrodeposition). Controlling the potential/current level defines how the material will form on the surface of the substrate. Other variables can be controlled to get the best formation of the material, such as temperature, pressure and deposition time.

The first manufacturing step consists of preparing the substrate for deposition. The process starts cutting off FTO plate, which comes from the factory in a  $10\times 10$  cm plate, to standardize the size of the electrodes and so that they fit in the electrochemical cell to carry out the deposition and subsequent analysis. The electrodes manufactured on FTO substrate were sized in rectangles of approximately  $1.5 \times 2.5$  cm, as shown in Figure 1a.

1. NiP precursor solution



2. CoP precursor solution

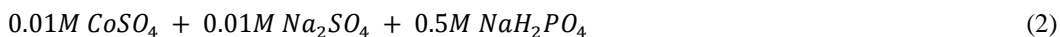
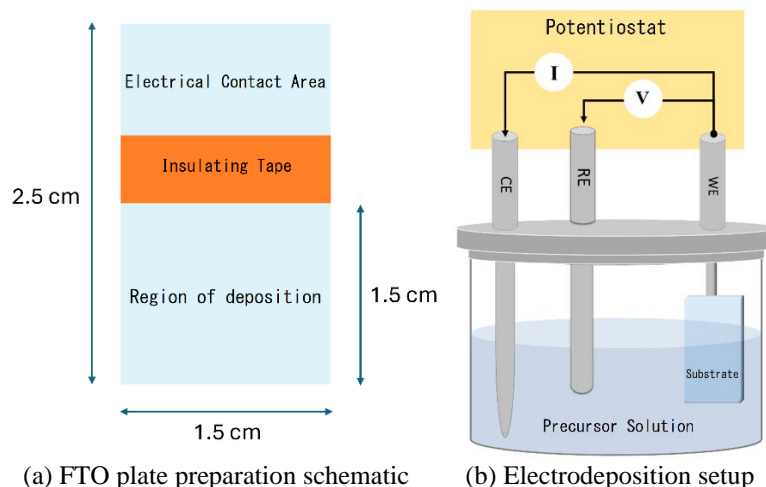


Figure 1b shown the fabrication setup using three-electrode electrochemical cell – counter electrode (CE) is a platinum plate, Ag/AgCl standard electrode is the reference electrode (RE) and a FTO glass connected as work electrode (WE). After precursor solutions preparation, as described in chemical Equations 1 and 2, electrodeposition of nickel phosphate (NiP) and cobalt phosphate (CoP) electrodes were conducted at -1.1V for 300s and room temperature.



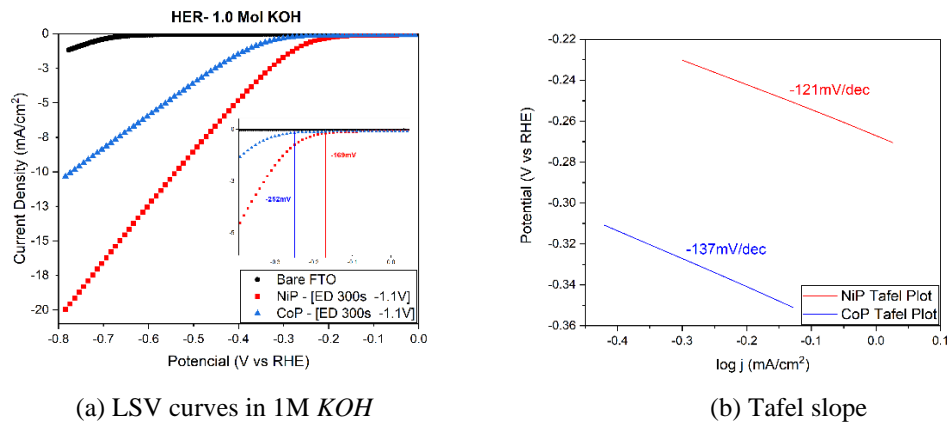
**Figure 2:** Structure of FTO samples and their application for electrodeposition using a three-electrode electrochemical cell and potentiostat.

Finished the electrodes fabrication step, all samples were characterized electrochemically by Linear Sweep Voltammetry (LSV) using an AutoLab PGSTAT204 potentiostat, and morphological by Scanning Electron Microscope (SEM) - Jeol JSM 7100F - and Atomic Force Microscope (AFM) - Nanosurf easy scan 2.

### 3. Results and Discussion

#### 3.1. Electrochemical Analysis

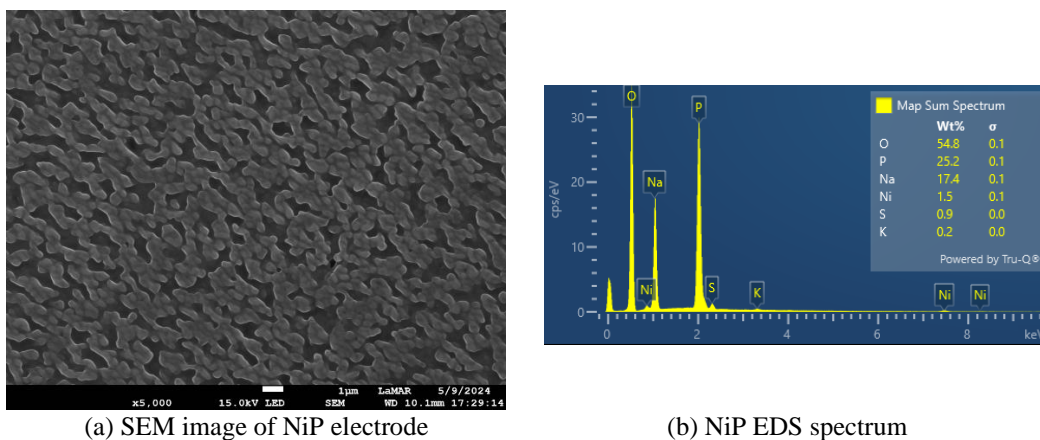
LSV curves were got from NiP and CoP films in electrolyte of 1M of KOH with three-electrode electrochemical cell, as described in Section 2 for the electrodeposition setup. This was the first analysis step conducted to evaluate of HER performance of each electrode. Figure 2 shows the comparison of results obtained with bare FTO, NiP and CoP. Figure 2a shown the results of HER performance got with LSV curves. The result of NiP electrode indicated that hydrogen reaction starts at -169 mV *versus* -252 mV of the CoP. The comparison of Tafel slope is showed in Figure 2b and NiP electrode got better result with -121 mV/decade and CoP electrode reached -137 mV/decade. The electrochemical results showed the higher electrocatalytic activity of NiP electrode with low overpotential and Tafel slope when comparison of CoP.



**Figure 2:** Electrochemical results from NiP, CoP and bare FTO electrode in saturated 1M KOH at 25°C.

### 3.2. Scanning Electron Microscope Characterization

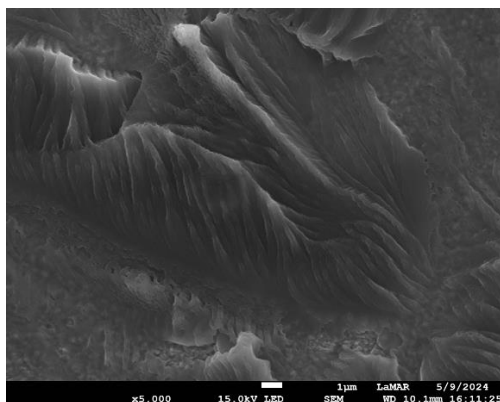
The morphological characterizations were carried out through SEM images and EDS spectra. Figure 3 shows the results of the NiP sample.



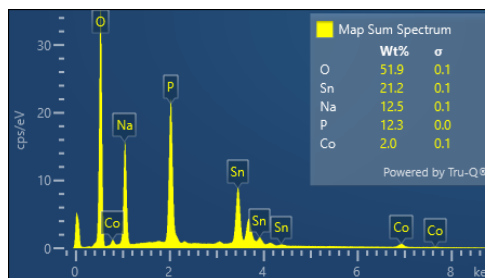
**Figure 3:** Morphological characterization - SEM image and EDS spectrum of NiP electrode.

Figure 3a shows the micrograph of the nickel phosphate electrode at 5,000x magnification, in which it is possible to observe the formation of a porous structure. Porosity leads to an increase in the surface area of the electrode and has been reported in the literature as being responsible for the increase in the electrocatalytic activity of the material (Zhou, et al., 2016).

EDS spectrum of the material was plotted in Figure 3b and shows the composition of the electrode in weight percent. The spectrum of the NiP sample shows that the expected elements are present in the composition of the material - oxygen, phosphorus and nickel. There is also a peak corresponding to sodium due to contamination with residues from the precursor solution.



(a) SEM image of CoP electrode



(b) CoP EDS spectrum

**Figure 4:** Morphological characterization - SEM image and EDS spectrum of CoP electrode.

SEM analysis of the CoP sample shows that there is no porosity on the surface, as well shown in Figure 4a. This may explain the reduction in catalytic activity of this material when compared to the NiP film.

As explained in the EDS analysis obtained from the NiP electrode, in the spectrum of the CoP electrode there is also a peak indicating sodium residues from the precursor solution. The presence of oxygen, phosphorus and cobalt are also shown, but in this sample, the peaks are related to tin from the FTO glass substrate, as denoted in Figure 4b.

## 4. Conclusions

In summary, we have demonstrated the catalytic efficiency of metal phosphates like nickel phosphate (NiP) and cobalt phosphate (CoP) on FTO glass for hydrogen evolution reactions (HER). These thin-film metal phosphates, with their abundant defects, facilitate rapid electron transport and high exposure to accessible active sites. The NiP electrode obtained low overpotential, at -169 mV, and high current density, indicating to be a promising material to conduct advanced future studies with other simple phosphates or bi-metallic nickel-based electrodes. This study may pave the way for designing spinel oxides with superior electrocatalytic activity for energy conversion applications.

## Acknowledgments

A.L.F.B. acknowledge the Brazilian organizations CAPES, CNPq (Bolsa de Produtividade 30.7418/2021-9 and 30.4511/2022-6) and FAPERJ (E-26-210.965/2021, E-26-210.801/2021, E-26-245.307/2019, E-26-202.549/2019, E-26/201.934/2019, E-26-200.320/2023, and E-26/201.622/2023), FINEP (Convênio nº 04.19.0040). J.A.R. thanks the CAPES FUC-01, J.V.M and T.O.B. thanks the CNPq scholarship and R.S.B. to Faperj (E-26/202.465/2023 (293937)) and CAPES (88887.798322/2022-00).

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# Hydrothermal synthesis of copper cobalt oxide nanosheets for efficient electrocatalytic hydrogen generation

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## Abstract

The hydrogen evolution reaction (HER) through electrocatalysis of water splitting is crucial for producing green hydrogen. This paper details the synthesis of copper cobalt oxide (CuCo<sub>2</sub>O<sub>4</sub>) nanosheets via a hydrothermal method. Characterization techniques such as XRD, FESEM, EDS, TEM, XPS and electrochemical studies were used to evaluate the material's performance in HER. The morphological analysis revealed nanosheets with an average particle size of ~20 nm. These nanosheets exhibited overpotential of 346 mV, lower than other metal oxide nanosheets, and a Tafel slope of 73 mV/dec. In an alkaline KOH solution, the CuCo<sub>2</sub>O<sub>4</sub> nanosheets demonstrated superior electrocatalytic behavior and enhanced catalytic stability for HER. These findings suggest that CuCo<sub>2</sub>O<sub>4</sub> nanosheets could significantly contribute to future energy technology.

## 1. Introduction

Water splitting, which generates renewable hydrogen fuel, has become a crucial method for producing sustainable energy to address the decline in conventional energy sources and environmental pollution (Lado, et al., 2015). In water splitting, the oxygen evolution reaction (OER) acts as the counter reaction to the hydrogen evolution reaction (HER). As the cathodic half-reaction of electrochemical water splitting, the hydrogen evolution reaction (HER) is one of the simplest and cleanest methods for producing hydrogen (Lado, et al., 2015; Dong, et al., 2018). This process typically occurs under alkaline or acidic conditions, with alkaline media preferred for industrial applications due to the scarcity of low-cost oxygen evolution reaction (OER) catalysts for the anode in acidic environments (Gong, Wang, Chen, Hwang, & Dai, 2016; Bai, Li, Mao, Li, & Dong, 2016). However, HER efficiency is generally lower in alkaline solutions compared to acidic ones, despite similar reaction pathways in both media (Deng, Wang, Nie, & Wei, 2017; Danilovic, et al., 2012). Initially, hydrogen intermediates (Had) form on the catalyst surface during the Volmer step, followed by either electrochemical desorption (Heyrovsky step) or recombination (Tafel step) to generate molecular hydrogen (Danilovic, et al., 2012;

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<sup>1</sup> Thanks for Sathyabama Institute of Science and Technology

<sup>2</sup> Thanks to Brazilian research funding agencies Capes, CNPq and FAPERJ

Zhang, et al., 2017; Song, et al., 2018; Zhu, et al., 2020). The key difference is that  $H_{ad}$  forms from different reacting species in acidic ( $H_3O^+$ ) and alkaline ( $H_2O/OH^-$ ) media through electron transfer, with water dissociation being slower in alkaline solutions than in acidic environments (Deng, Wang, Nie, & Wei, 2017; Danilovic, et al., 2012; Zhang, et al., 2017). Thus, enhancing HER activity in alkaline media requires improving water dissociation and accelerating  $H_{ad}$  formation.

Metal oxides have garnered significant attention from researchers due to their compositional and structural diversity, tunability, low cost, abundance, and environmental friendliness as electrocatalysts (Song, et al., 2018; Zhu, et al., 2020). However, pristine metal oxides have proven unsatisfactory for practical applications in the HER, primarily due to unfavorable intermediate binding strength and stability issues (Cho, Yu, Lee, Kim, & Lee, 2018; Adamson, et al., 2020). Bimetallic oxides have emerged as a promising strategy to enhance the use of metal oxides as HER electrocatalysts, retaining their unique properties while offering optimized adsorption energies and surpassing the intrinsic catalytic activity limits of pristine metal oxides. This results in higher HER efficiency (Lv, Xu, Yang, Huang, & Zhang, 2019; Suryanto, Wang, Hocking, Adamson, & Zhao, 2019) and significantly improved stability in aqueous environments and alkaline electrolytes (Bates, Jia, Ramaswamy, Allen, & Mukerjee, 2015; Cho, Yu, Lee, Kim, & Lee, 2018). Compared to other mixed metal-based ceramic materials, heterostructured metal oxides also present a cost-effective solution for industrial applications due to their facile synthesis and lower noble metal loading (Seuferling, Larson, Barforoush, & Leonard, 2021; Nie, et al., 2022; Pagliaro, et al., 2022). Nonetheless, there is still no clear guideline for the use of bimetallic oxides as HER electrocatalysts.

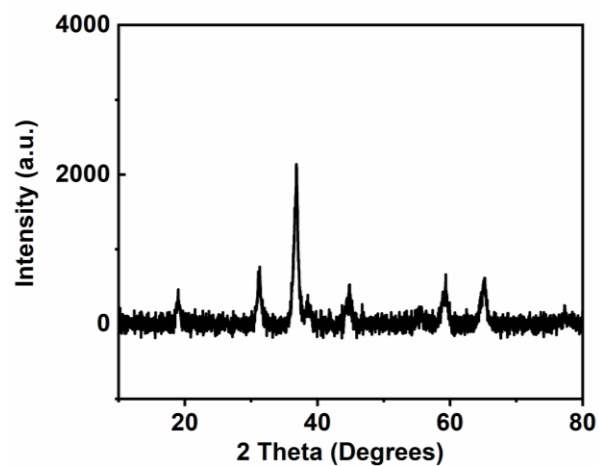
In this paper, we report a simple and inexpensive hydrothermal synthesis of two-dimensional  $CuCo_2O_4$  nanosheets using sodium dodecyl sulfate (SDS) as surfactant. The as-synthesized  $CuCo_2O_4$  displayed an activation period during the HER in alkaline electrolyte and finally reached a superior performance with overpotential of 346 mV to start the reaction. The synergistic effect of 2D bimetallic oxide nanosheets sample has smaller Tafel slope and lower overpotential, which improves the catalytic activity of hydrogen evolution.

## 2. Experimental

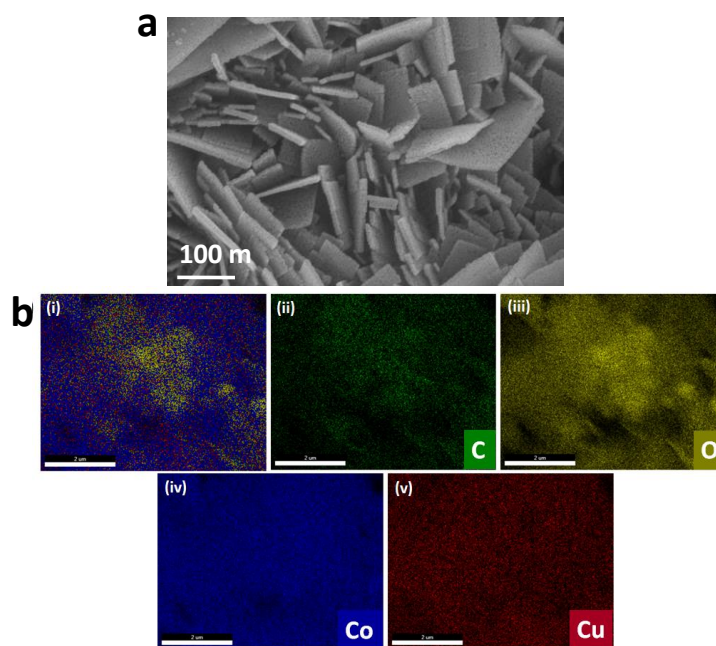
All reagents used were of analytical grade. In brief, 1 mmol of  $Cu(NO_3)_2 \cdot 3H_2O$  and 2 mmol of  $Co(NO_3)_2 \cdot 6H_2O$  were dissolved in a 100 mL beaker containing equal volumes of water and ethanol, followed by sonication for complete dissolution. Then, 300 mg of Sodium dodecyl sulfate (SDS) was dissolved in a water-ethanol mixture (1:1 v/v) and added to the initial solution under sonication. Separately, 12 mmol of urea was dissolved in water and ethanol (1:1 v/v), added to the mixture, and sonicated for 30 minutes. The reaction mixture was transferred to a 100 mL Teflon-lined autoclave and heated at 140 °C for 24 hours. After cooling to room temperature, the green precipitate was washed multiple times with water and ethanol via centrifugation at 4000 rpm, collected, and dried at 60 °C. The dried sample was then calcined at 350 °C for 3 hours.

## 3. Results and Discussion

Figure 1 shows typical wide-angle XRD patterns of  $CuCo_2O_4$  nanosheets. The  $2\theta$  angles of the characteristic peaks match the JCPDS data (JCPDS 001-1155), indicating a cubic spinel  $CuCo_2O_4$  crystalline structure. No peaks for CuO, CoO,  $CoO_2$ , or Co were detected, confirming the high purity of the synthesized  $CuCo_2O_4$  samples. The broad XRD peaks suggest nanometer-sized crystallites, and the average crystalline size of  $CuCo_2O_4$  was determined to be approximately 26 nm using the Debye-Scherrer equation.



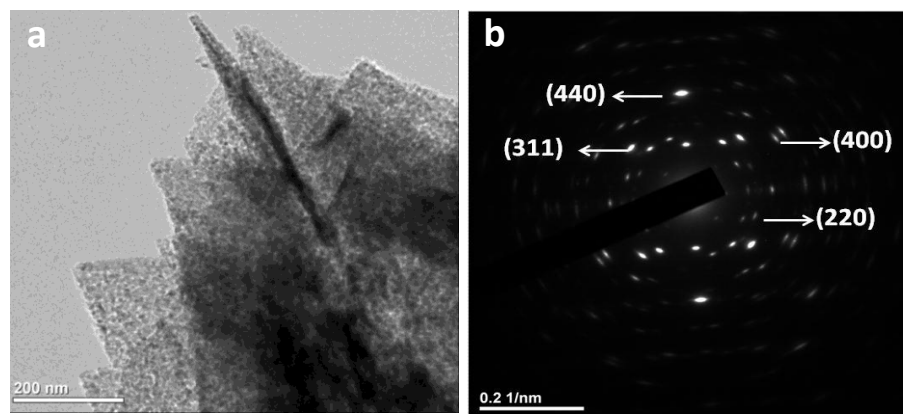
**Figure 3:** XRD pattern of  $\text{CuCo}_2\text{O}_4$  nanosheets.



**Figure 2:** (a) FESEM image and (b) elemental mapping of  $\text{CuCo}_2\text{O}_4$  nanosheets.

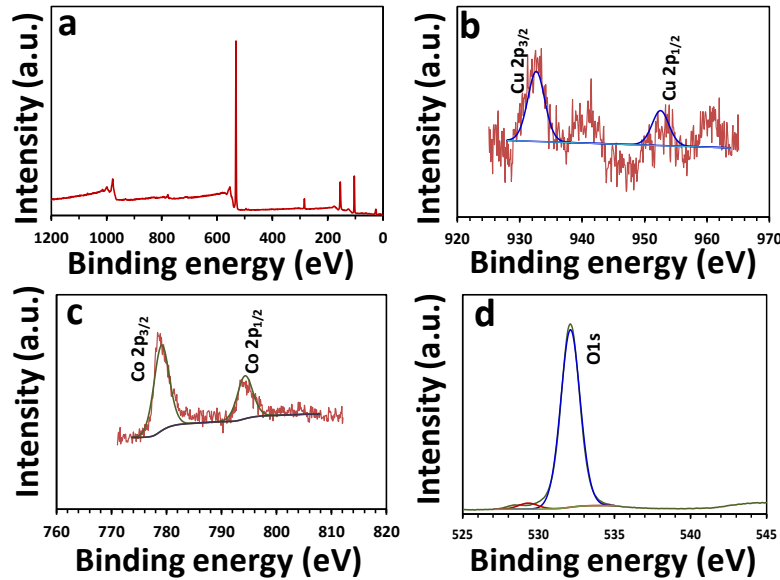
The morphology of the synthesized  $\text{CuCo}_2\text{O}_4$  nanosheets was examined by FESEM. Figure 2a presents high-magnification FESEM images of  $\text{CuCo}_2\text{O}_4$  nanosheets, revealing a porous nanosheet structure formed through hydrothermal synthesis at  $140\text{ }^\circ\text{C}$  for 24 hours. The enlarged image shows that these porous nanosheets are made up of nanoparticles smaller than 10 nm, with an approximate thickness of 20 nm. Figure 2b shows elemental mapping confirmed the presence of Cu, Co, and O in the material, with a Co to Cu atomic ratio of roughly 2:1 was confirmed with EDS measurements.

The structural features of the prepared  $\text{CuCo}_2\text{O}_4$  nanosheets samples were examined by HRTEM and selected area electron diffraction (SAED), as shown in Figures 3a and 3b. HRTEM images confirmed the nanosheet-like morphology of the  $\text{CuCo}_2\text{O}_4$  samples, with porous sheets measuring less than  $3\ \mu\text{m}$  in length and about  $1\ \mu\text{m}$  in width, consistent with the FESEM images. The rough, porous surface of the nanosheets results from various factors, including nucleation, grain growth, oriented attachment, Ostwald ripening, the concentration of the shape-directing agent, and hydrothermal parameters (temperature and duration). SDS played a crucial role as a structure-directing agent, controlling the size and surface free energy, leading to seed-mediated and shape-controlled growth of  $\text{CuCo}_2\text{O}_4$  nanosheets. The SAED patterns showed well-defined diffraction rings, indicating the polycrystalline nature of the cubic face, and these rings could be indexed to the (220), (311), (400), and (440) planes of the cubic  $\text{CuCo}_2\text{O}_4$  phase, consistent with XRD results.



**Figure 3:** (a) TEM image and (b) SAED pattern of  $\text{CuCo}_2\text{O}_4$  nanosheets.

The elemental composition and oxidation state of the prepared  $\text{CuCo}_2\text{O}_4$  nanosheets materials were examined by XPS. The complete survey spectrum (Fig. 4a) revealed the presence of C, O, Cu, and Co, with no contamination. The high-resolution XPS spectrum of Cu 2p (Fig. 4b) showed two main peaks at 933.4 and 953.2 eV, corresponding to Cu 2p<sub>3/2</sub> and Cu 2p<sub>1/2</sub>, respectively, along with two shake-up satellite peaks at 941.6 and 961.3 eV. For Co 2p (Fig. 5c), peaks at 779.08 and 794.6 eV were identified as Co 2p<sub>3/2</sub> and Co 2p<sub>1/2</sub>, respectively, with a spin-orbit splitting of about 15.0 eV. Additional satellite peaks were observed at 788.5 and 804.4 eV. Peaks at 779.2 and 794.5 eV were associated with the Co<sup>3+</sup> oxidation state, while peaks at 781.6 and 796.4 eV indicated the Co<sup>2+</sup> state. The O 1s spectrum (Fig. 5d) could be deconvoluted into three peaks: O-1 at 528.9 eV (oxy-metal bonding), O-2 at 530.5 eV (high defect sites with minimal O<sub>2</sub> coordination and small grain size), and O-3 at 532.2 eV (chemically and physically adsorbed H<sub>2</sub>O molecules).



**Figure 4:** XPS spectra of as-synthesized  $\text{CuCo}_2\text{O}_4$  nanosheets (a) survey spectrum, deconvoluted spectra of (b) Cu 2p, (c) Co 2p and (d) O 1s.

The cyclic voltammetry (CV) analysis of the potential charge storage mechanism for the  $\text{CuCo}_2\text{O}_4$  nanosheets working electrode behavior was performed, and the results are displayed in Fig. 5a. The amount of charge stored in the working electrode is represented by the integrated area under the CV curve at various scan rates ranging from 10 mV/s to 100 mV/s. The CV curves clearly show detectable oxidation and reduction peaks, which are due to the insertion and de-insertion of electrolyte ions during the anodic and cathodic reactions, respectively.

The catalytic characteristics of  $\text{CuCo}_2\text{O}_4$  nanosheets electrodes for the HER (Hydrogen evolution reaction) performance were closely measured as shown in Fig. 5b. To understand the HER properties of the electrodes, linear sweep voltammetry (LSV) was performed at a scan rate of 5 mV/s. The overpotential ( $\eta$ ) after the LSV plot can be determined from the equation 1.

$$\eta = E_{\text{RHE}} - 1.23 \text{ V} \quad (1)$$

$$E_{\text{RHE}} = E_{\text{SCE}} + 0.059 \text{ pH} + E^0_{\text{SCE}} \quad (2)$$

Where,  $E_{\text{RHE}}$  - Standard potential of the reversible hydrogen electrode,  $E_{\text{SCE}}$  - Standard potential of the saturated calomel electrode.

By using the above equation, the overpotential value for  $\text{CuCo}_2\text{O}_4$  nanosheets was found to be 346 mV, as shown in Fig. 5b. It was observed that the overpotential for the  $\text{CuCo}_2\text{O}_4$  nanosheets is lower than that of the pristine NH nanomaterial, and it possesses a higher current. These values correlate with the electrochemical surface area (ECSA) results, indicating that the  $\text{CuCo}_2\text{O}_4$  nanosheets electrode has a larger catalytic active area, where electrochemical reactions can be carried out for better HER performance.

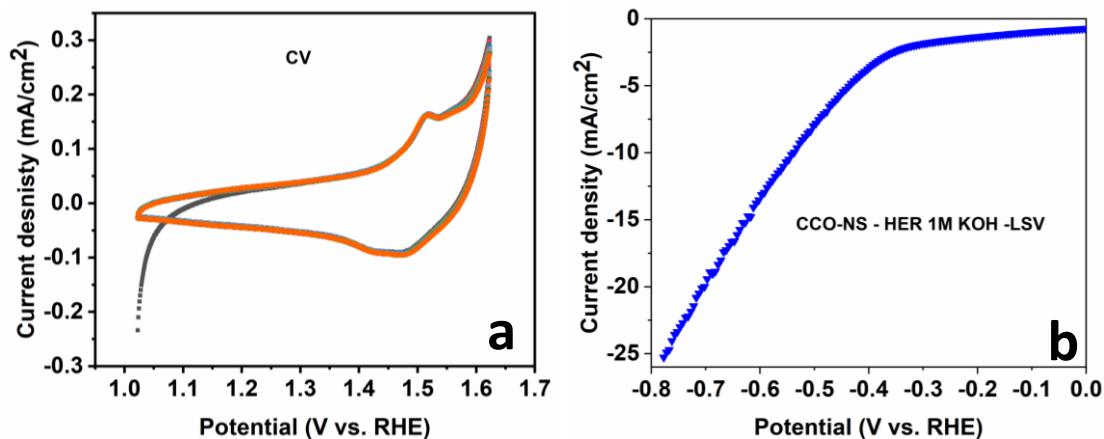


Figure 5: CV and LSV curves of CuCo<sub>2</sub>O<sub>4</sub> nanosheets in 1 M KOH at the scan rate of 10 mV/s for HER studies.

By using the above equation, the overpotential value for CuCo<sub>2</sub>O<sub>4</sub> nanosheets was found to be 346 mV, as shown in Fig. 5b.

The electrochemical reaction rate, represented by the Tafel plot, is closely related to the overpotential. The relation can be represented as:

$$\eta = b \log(j) + a \quad (3)$$

Where  $\eta$  is the overpotential,  $j$  is the current density, and  $a$  and  $b$  are fitting parameters. From the calculation using the  $\eta$  values, the smaller Tafel slope for the CuCo<sub>2</sub>O<sub>4</sub> nanosheets was found to be 73 mV/dec as shown in Fig. 6. This indicates a more efficient electrochemical reaction rate compared to other materials.

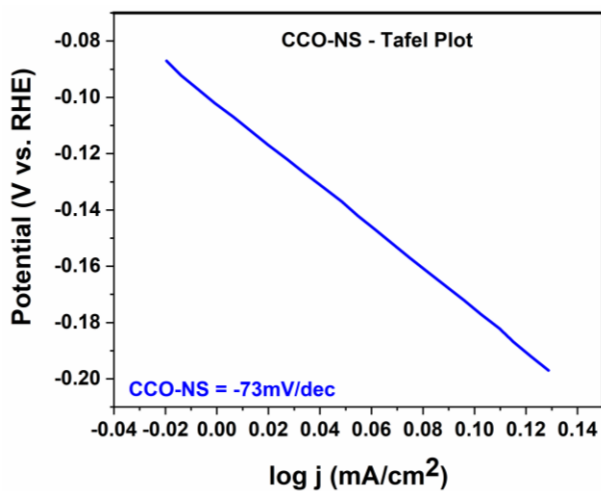


Figure 6: Tafel plot of CuCo<sub>2</sub>O<sub>4</sub> nanosheets.

## 4. Conclusion

In summary, two-dimensional  $\text{CuCo}_2\text{O}_4$  nanosheets positive electrode with a porous, uniform architecture was prepared using a simple and cost-effective single-step hydrothermal method. The  $\text{CuCo}_2\text{O}_4$  nanosheets significantly enhance water splitting, leading to a substantial yield of hydrogen in an alkaline solution. The HER performance of  $\text{CuCo}_2\text{O}_4$  nanosheets is notably improved, with a lower overpotential of 346 mV and the smallest Tafel slope of 73 mV/dec. Additionally, the HER activity of  $\text{CuCo}_2\text{O}_4$  nanosheets was monitored for a period of 5 hours, demonstrating its exceptional durability and longevity as an electrocatalyst.

## Acknowledgments

Dr. Y. Sasikumar acknowledges Dr. Mariazeena Johnson, the Chancellor, Sathyabama Institute of Science and Technology (Deemed to be University), Chennai for her kind support to carry out this research work. Dr. R. Suresh Babu wishes to acknowledge the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) for the financial support (88887.798322/2022-00) and Fundação de Amparo à Pesquisa do Estado do Rio de Janeiro (FAPERJ) for the financial support of senior post-doctoral fellow (E-26/202.465/2023 (293937)). Dr. A.L.F de Barros acknowledge the Brazilian organizations CAPES, CNPq (Bolsa de Produtividade 30.7418/2021-9 and 30.4511/2022-6) and FAPERJ (E-26-210.965/2021, E-26-210.801/2021, E-26-245.307/2019, E-26-202.549/2019, E-26/201.934/2019, E-26-200.320/2023, and E-26/201.622\|2023), FINEP (Convênio n° 04.19.0040). J.A.F.C Rodrigues thanks the CAPES FUC-01 scholarship.

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# Transitioning Santiago Island to a Renewable Energy Based system

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## Abstract

Cape Verde, an archipelago nation in the Atlantic Ocean, faces significant challenges in meeting its energy demands due to its dependence on imported fossil fuels. Through extensive data collection, this study evaluates the future state of renewable energy deployment, including the penetration levels of photovoltaic and wind renewable sources and their contribution to the overall energy supply on the island. The research involves analyzing the integration of RES into the grid with hourly data on generation throughout the year and by seasons, using the EnergyPLAN energy system computer modeling tool. Additionally, it examines the system's behavior given potential demand growth, and considers the integration of green hydrogen as a possible form of energy storage. This study aims primarily at critically assessing the scenarios outlined in the energy plan proposed by the government of Cape Verde, with the objective of identifying alternative solutions that offer substantial improvements.

Keywords: Renewable Energy Source · Energy Planning · Photovoltaic Power · Wind Power · Green Hydrogen · Energy Storage.

## 1. Introduction

The global energy transition towards sustainable sources is imperative in addressing the escalating concerns of climate change and environmental degradation. This shift from fossil fuels to renewable energy sources (RES) is crucial for reducing greenhouse gas emissions, enhancing energy security, and fostering economic resilience (Gielen et al., 2019). Effective energy planning is fundamental in this transition, ensuring the integration of RES into the energy grid is efficient, sustainable, and reliable. Strategic energy planning not only facilitates the optimal deployment of renewable technologies but also helps in addressing the technical, economic, and policy challenges associated with the energy transition (Lund et al., 2021).

One of the primary challenges associated with renewable energy is its reliance on stochastic sources. Photovoltaic and wind energy, for instance, are inherently variable and intermittent, which poses significant challenges to maintaining a stable and reliable power supply (Notton et al., 2018). To address this variability, several solutions have been explored, with energy storage systems emerging as particularly promising in recent years. These systems capture surplus energy generated during periods of low demand or high production and release it when demand exceeds production, thus smoothing out the fluctuations inherent in RES (Vivas et al., 2018).

Several energy storage technologies are pivotal in addressing these challenges. Electrochemical storage, including batteries and fuel cells, offers high efficiency and rapid response times, making it suitable for a range of applications from residential to grid-scale storage. Mechanical storage technologies, such as pumped hydro storage and compressed air energy storage, are well-suited for large-scale energy storage, providing significant capacity and long-duration storage capabilities (Gür, 2018). Among these, green hydrogen stands out due to its potential for large-scale storage and its role in facilitating the transition to a hydrogen economy. Green hydrogen, produced through the electrolysis of water using renewable energy, offers a sustainable and versatile energy carrier that can be utilized across various sectors (Hosseini & Wahid, 2016).

Cape Verde, an archipelago off the northwest coast of Africa, presents a unique case for renewable energy implementation, particularly on Santiago Island, the largest and most populous island. Despite its substantial potential for photovoltaic and wind energy, Cape Verde heavily relies on imported fossil fuels, making energy independence a national priority (Pombo, et al., 2023). The government has devised an ambitious plan to transition towards renewable energy, structured into three distinct phases. The first phase aims to enhance the electrical grid by 2025 to achieve 30% RES power generation. The second phase, targeted for 2030, seeks to increase the share of RES to 50%, focusing on expanding RES capacity and deploying advanced storage solutions. The final phase, envisioned for 2040, aims for nearly 100% RES power generation, incorporating advanced technologies such as smart grids and regional energy networks (Imprensa Nacional de Cabo Verde, 2019).

Santiago Island, responsible for nearly half of Cape Verde's energy consumption, grapples with high energy losses and a minimal share of renewables in its energy mix, with only 15% of its electricity derived from renewable sources. Specifically, wind and photovoltaic energy contribute just 12% and 3% respectively, underscoring the island's heavy reliance on fossil fuels (Electra, 2021). Despite this, Santiago has substantial potential for renewable energy, particularly from wind and solar resources. These resources peak from January to June but experience a notable decline in the summer months, especially for photovoltaics due to increased cloudiness during the wet season (Pombo et al., 2023).

This work will analyze the integration of renewable energy sources (RES) into the grid, examine the system's behavior given potential demand growth, and consider the integration of green hydrogen as a possible form of energy storage. The EnergyPLAN model (Lund, 2022) will be applied exclusively to Santiago Island to facilitate detailed analysis of different energy scenarios, allowing for the assessment of various strategies to achieve higher renewable energy integration and improved energy system performance.

The choice of Santiago Island for this study is due to its strategic importance and its potential to serve as a blueprint for renewable energy implementation across the archipelago. By modeling the energy system of Santiago Island, this study aims to identify the most effective pathways for integrating renewable energy and deploying green hydrogen storage, ultimately contributing to the island's green energy future.

The paper is organized as follows: Section 2 provides background on the project by reviewing relevant previous work. Section 3 details the methodology for the case study, outlining data collection methods and the tools used. Section 4 validates the accuracy of the EnergyPLAN tool by comparing its simulated energy production values for Santiago Island in 2022 with the actual recorded data for that year. Section 5 presents the results of the simulations, including comparisons across multiple scenarios to evaluate their effectiveness. Finally, Section 6 summarizes the key findings and suggests directions for future research.

## 2. Previous works

The previous study, titled “Empowering Santiago Island: Renewable Energy Integration in Cape Verde” and presented at the Symposium of Applied Science for Young Researchers (SASYR), was authored by the same team responsible for this paper. This earlier research provided a foundational basis for initial data collection and analysis. The current study represents an in-depth extension of this previous work, aiming to complement and enhance the initial findings through the integration of new data and the application of diverse analyses and alternative approaches.

This research broadens the scope of the investigation in several key areas. By incorporating new data that was not available in the earlier study, the research has uncovered additional patterns and correlations. Furthermore, the validation of the EnergyPLAN model using 2022 data has confirmed its accuracy in simulating energy production on Santiago Island.

## 3. Methodology

EnergyPLAN is a bottom-up simulation tool designed to model and predict power generation capabilities of energy systems over the course of a year. To function effectively, it requires a comprehensive set of input data, including annual figures for energy consumption, importation, and exportation. Additionally, detailed information about each energy source in the system is needed, such as installed capacity and capacity factors.

The tool also depends on precise hourly distribution data for each energy resource, including solar irradiance for photovoltaic systems and wind speed for wind power. This data is essential for the simulation process, as EnergyPLAN uses it to allocate energy generation on an hourly basis throughout the year.

The software generates outputs that include detailed hourly data as well as aggregated annual and monthly summaries. These outputs reflect the expected power generation based on the input data and the software’s internal priorities, without providing direct analyses of the broader environmental or economic impacts of various energy strategies.

To model the energy system for the islands in the EnergyPLAN software, the following sources and tools were utilized for data collection:

- **Renewables.ninja:** This tool provides meteorological data, including wind speeds and solar irradiance, and estimated capacity factors for energy production from both photovoltaic (PV) and wind facilities (Pfenninger & Staffell, 2016).
- **Cape Verde Official Bulletin:** Data on the islands’ installed capacities and annual energy consumption for the 2030 scenario were gathered from this bulletin (Imprensa Nacional de Cabo Verde, 2019).
- **Load Diagram:** A detailed load diagram, available from a related study conducted by a researcher on the islands of São Vicente and Santiago, was used in this analysis. This diagram offers a comprehensive representation of daily energy consumption patterns throughout the year, effectively capturing seasonal variations (Pombo, 2022).
- **Electra S.A. Report:** Data from this report were used to model the islands’ installed capacities and annual energy consumption. These data were crucial for validating the EnergyPLAN tool using real values (Electra S.A., 2022).

To model the 2030 energy scenario for Santiago Island, energy source capacities (thermal, wind, and photovoltaic) were based on projections from the Cape Verdean governmental bulletin, which describes a business-as-usual scenario. It was assumed that Santiago Island would have 40% of the total installed capacity for Cape Verde, aligning with its expected share of national energy consumption

## 4. Validation

To evaluate the accuracy and reliability of the EnergyPLAN model, a comprehensive validation was conducted using actual energy production data from Santiago Island for the year 2022. This validation involved comparing the model’s simulated outputs with the real-world production data provided by Electra S.A., the primary energy provider for the island.

The validation focused on three key energy sources: thermal, wind, and photovoltaic (PV). The annual production figures for these sources, as reported by Electra S.A., are detailed in Table 1. This table juxtaposes the EnergyPLAN model’s predictions with the actual reported values, illustrating the model’s performance in forecasting energy production.

	<b>Thermal (GWh/year)</b>	<b>Wind (GWh/year)</b>	<b>PV (GWh/year)</b>
<b>Electra S.A. data</b>	224.00	29.80	6.30
<b>EnergyPLAN data</b>	<b>225.38</b>	<b>28.09</b>	<b>6.71</b>

**Table 1:** Comparison of Annual Energy Production from Thermal, Wind, and PV Sources: 2022 Electra S.A. Report vs. EnergyPLAN.

To assess the model’s accuracy, percentage errors between the simulated data and actual production values were calculated, as shown in Table 2. These errors represent the deviation of the simulated data from the actual production values. The analysis of these percentage errors provides insight into how closely the EnergyPLAN model’s predictions align with observed data.

Thermal (%)	Wind (%)	PV (%)
0.61	5.84	6.02

**Table 2:** Percentage Errors in EnergyPLAN Model Simulations (2022).

The results indicate that the EnergyPLAN model’s predictions are in close agreement with the actual production data. Specifically, the percentage errors for thermal, wind, and PV energy sources were found to be within acceptable ranges, demonstrating that the model can reliably simulate energy production scenarios, confirming model efficacy in accurately representing energy production.

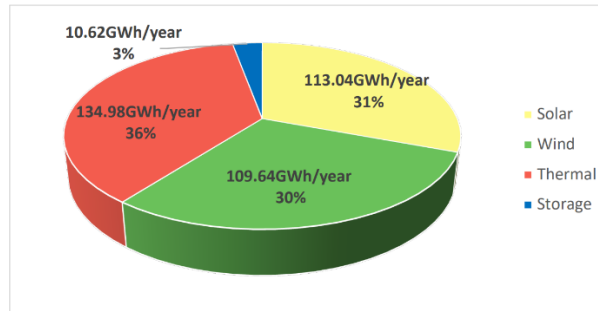
## 5. Results and Discussion

The 2030 scenario was modelled using values based on the official bulletin and incorporating a storage solution utilizing green hydrogen. Although the storage solution currently representing low values of overall efficiency around 30% - 40%, the choice of hydrogen storage was made to further reduce reliance on fossil fuels and to mitigate carbon emissions (DiChristopher, 2024).

The storage capacity was set to 40% of the available capacity for Cape Verde, aligning with Santiago Island’s energy consumption as a proportion of the country’s total energy consumption.

The EnergyPLAN model of the 2030 scenario predicted an energy production of 368.28 GWh on Santiago Island, resulting in an overproduction of 31.28 GWh without the implementation of a storage solution. After incorporating the green hydrogen energy storage, the surplus energy production was reduced to 0.74 GWh.

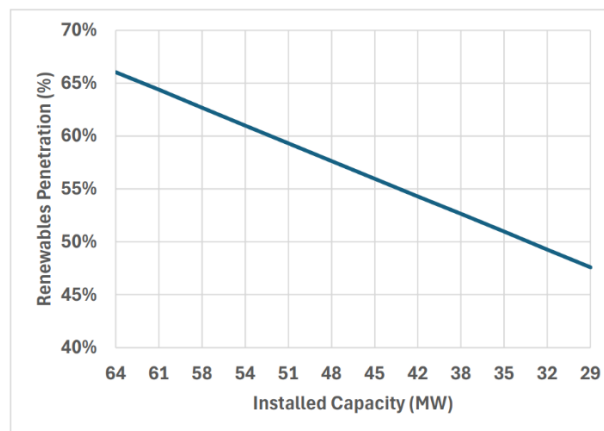
The energy production share from the sources is provided in the following Figure 1.



**Figure 1:** Distribution of Global Energy Consumption: RES vs. Thermal.

The EnergyPLAN model predicted a renewable energy share of 65.82% in the island’s electrical system, surpassing the initial target for the 2030 scenario as outlined in the official bulletin. It was observed that the implementation of the storage solution led to a reduction in the system’s thermal energy production, from 145.6 GWh to 134.98 GWh.

Figure 2 presents an analysis describing the relationship between PV installed capacity and the penetration of renewable energy sources (RES) in the island’s electrical grid. This analysis provides additional perspective on the improvements made to the 2030 scenario, offering insights into optimizing PV capacity for enhanced RES integration.

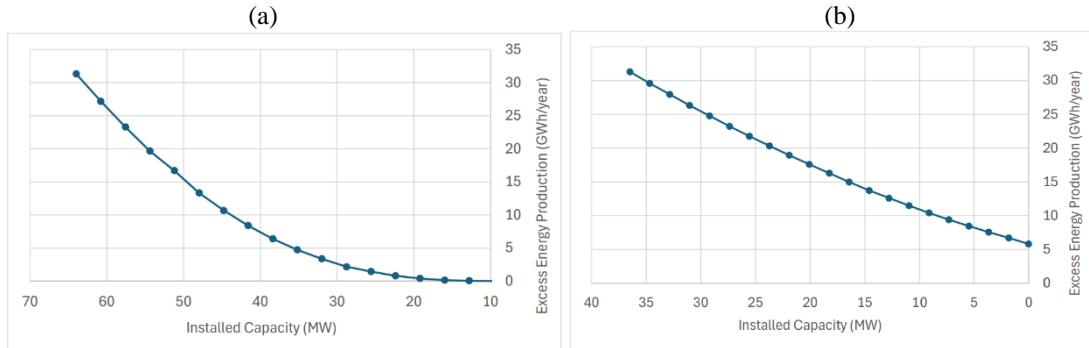


**Figure 2:** Installed PV capacity vs RES penetration with storage.

The data shows that a reduction of the PV installed capacity from 64 MW to 35.2 MW, the system still meets the goal of the 2030 scenario with 50.95% of RES penetration in the islands electrical grid.

A sensitivity analysis was conducted to evaluate the 2030 scenario for Santiago Island by examining the relationship between the installed capacities of photovoltaic (PV) and wind facilities and the resulting surplus energy production. This analysis, as demonstrated in Figure 3, provided insights into how different levels of renewable energy installations could affect the overall energy balance,

highlighting the importance of optimizing capacity to minimize energy waste and ensure efficient energy production and consumption.



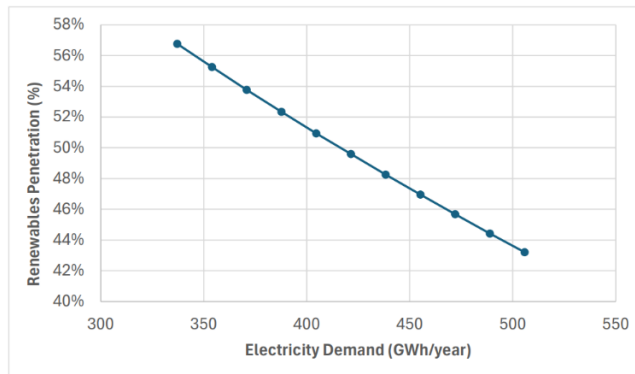
**Figure 3:** Installed PV capacity vs excess energy production (a) and Installed Wind capacity vs excess energy production (b).

The Figure 3a represents the relation between the PV installed capacity and the island’s excess energy production and the Figure 3b illustrates the relation between the installed wind capacity and excess energy production.

The Figure 3a indicates that reducing the installed PV capacity initiates a rapid decline in excess energy production. This phenomenon underscores the nonlinear relationship between PV capacity and excess energy production, where the pronounced reduction is related to the surplus of the RES energy production and the smaller reductions are related to the RES penetration into island’s electrical grid.

Figure 3b reveals a linear decreasing trend, indicating that reductions in installed wind capacity are proportional to reductions in excess energy production. According to the graph, even with zero installed wind capacity, there remains a notable amount of excess energy production.

Figure 4 represents an analysis conducted to study the system’s reliability and effectiveness by examining the relationship between electricity demand and the penetration of renewable energy sources (RES).



**Figure 4:** Electricity demand vs. RES penetration.

As electricity demand increases, there is an expected decrease in the penetration of renewable energy sources (RES) in the island’s electrical grid. This is due to the increased need for thermal energy production and a fixed renewable energy production capacity.

The system was able to sustain a goal of 50% renewable energy penetration in the electrical grid up to an increment of approximately 404 GWh, demonstrating a well-structured and reliable system.

## 6. Conclusion

The study on Santiago Island demonstrates the potential for significant renewable energy integration to reduce dependence on imported fossil fuels.

By leveraging tools like EnergyPLAN and data sources such as Renewables.ninja, Cape Verde's Official Bulletin, and reports from Electra S.A., the research successfully models the island's 2030 energy scenario. The validation of EnergyPLAN using real data from 2022 confirms its reliability for future energy planning.

The findings highlight the strategic importance of Santiago Island in Cape Verde's energy transition, showcasing pathways to achieve higher renewable energy penetration and improved energy system performance.

## Acknowledgement

The authors are grateful to the Foundation for Science and Technology (FCT, Portugal) for financial support through national funds FCT/MCTES (PIDDAC) to CeDRI, UIDB/05757/2020 (DOI: 10.54499/UIDB/05757/2020) and UIDP/05757/2020 (DOI: 10.54499/UIDP/05757/2020) and SusTEC, LA/P/0007/2020 (DOI: 10.54499/LA/P/0007/2020).

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# A Context-Aware Approach to Data Exchange in the Energy Sector

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## Abstract

This paper presents a novel approach to enhance data exchange within the energy sector by developing a context-aware method utilizing Natural Language Processing (NLP) techniques and ontologies such as Open Energy Ontology (OEO). The proposed solution addresses the challenges arising from differing contexts and perceptions, particularly among actors like ENTSO-E and its member countries. By capturing, representing, and assigning meanings based on the specific realities of the energy sector, this work seeks to minimize miscommunications and complications that may arise during data exchange. The approach is built upon previous research exploring ontology development and context perception.

## 1. Introduction

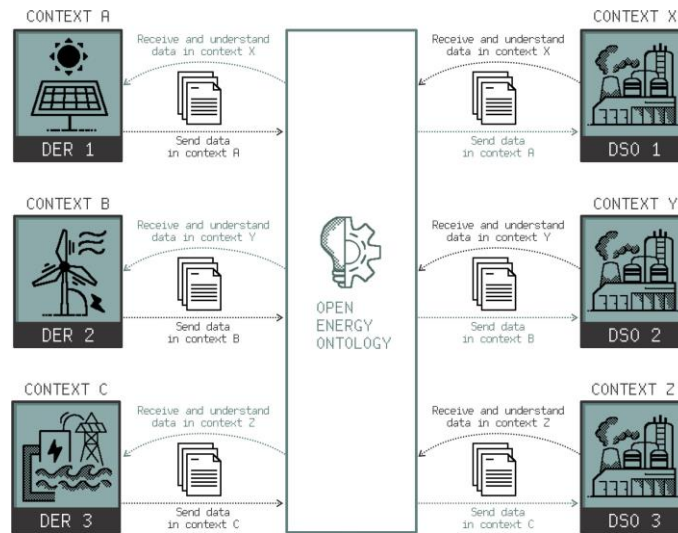
The release of IEEE's Smart Grid Report in 2015 (2015 IEEE Smart Grid Annual Report, n.d.) brought renewed attention to the topic of interoperability, especially concerning the energy field. Projects such as ENTSO-e's (ENTSO-E (European Network of Transmission System Operators for Electricity), n.d.) Tdx Assist (Tdx Assist, n.d.), for example, focused heavily on technologies used to interoperate between different actors of the sector, what protocols and what to be followed. Additionally, IRENA (International Renewable Energy Agency (IRENA), n.d.) gave special attention to the matter in its 2023 World Energy Transitions Outlook (World Energy Transitions Outlook 2023, n.d.).

Based on this scenario, it stands to reason that the task of interoperating actors inserted in different realities or contexts with different protocols and data formats may be prone to miscommunications. One such case may be present with ENTSO-e and the various countries under its umbrella, each with their specificities.

One such case, and the one addressed in this work, pertains to words that have different meanings, sometimes significantly changing what a piece of data should represent, depending on the context of the sender and the receiver of that piece of information. For the purposes of what is being proposed, context -as seen in Santos et al. (dos Santos, Tedesco, & Salgado, 2012) can be understood as a group of factors and situations that define the reality of an actor and how they perceive the world around them.

Literature shows that authors have been exploring this question from multiple angles (Booshehri et al., 2021; Kemp et al., 2023) and fields of application. For example, some approached it from the ontology perspective, working to create a model that could be used to exchange data in an open, structured, and sophisticated manner. Others focused on the realm of context and perception and how they are defined and influence each other (dos Santos et al., 2012).

The ever-expanding energy domain, with its many actors and factors involved, is subjected to several highly different contexts and perceptions. This is more pronounced in cases such as that of ENTSO-E and the countries under its umbrella, exchanging data with similar definitions but meanings that differ depending on the situations and characteristics of each one of them. That being the case, solutions focused on conveying the right meaning, according to an actor’s context, may be beneficial, especially when problems arising from misconceptions and miscommunications are concerned. Having the previously described scenario in mind, the main contribution regarding what is proposed in this work stems from decreasing the likelihood of miscommunications, or any complications created by them, happening. At the end of the process, this paper aims to set the foundations for a solution capable of addressing, in a broader sense, the effects and changes originating from the differences in context between energy sector actors. Figure 1 exemplifies this visually, with two actors exchanging data while the proposed solution, working alongside OEO, acts as a middleware, adjusting meanings based on the sender’s context.



**Figure 1:** Overall idea of the proposed contribution. Note two actors exchange data while the proposed solution, working alongside OEO, acts as a middleware.

The squares on the left represent Distributed Energy Resources (DERs). Here, they function as senders, embedding terms with meanings aligned with their contexts. On the right, Transmission System Operators (TSOs) are depicted, each with their own contexts. In the middle, the Open Energy Ontology (OEO) serves as a mediator capable of attaching any new information necessary to ensure smooth communication.

## 2. Methodology

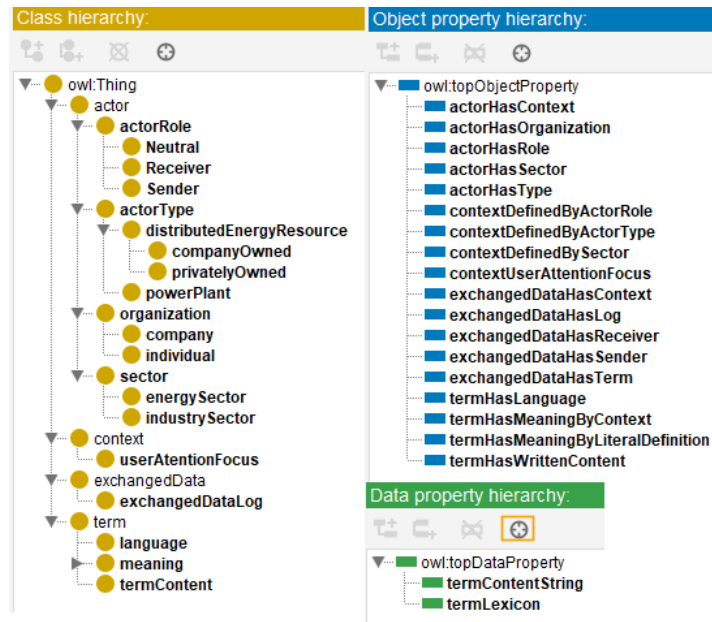
A single word can have multiple meanings based on context. This work aims to mitigate ambiguity by employing ontology to gather information about the data sender and Natural Language Toolkit (NLTK) to discern the meaning that best aligns with their specific context. This was accomplished in five sequential steps:

1. *Determining what ontology to use:* This step involves selecting an ontology that captures data related to the actors and their contexts, including spatial data and their respective sectors. The Open Energy Ontology (Booshehri et al., 2021) stands as a good example of this. For brevity's sake, this work will assume the ontology comprises fields named actorSector, actorContext, termLexicon, termHasMeaningByContext, and termContentString.
2. *Defining actors, context, and terms :* This step involves defining which actors will participate in the data exchange, determining the terms to be sent, and specifying the context in which their meanings will be conveyed.
3. *Defining what dictionaries to use:* This step involves defining the dictionaries where the meanings of words will be searched. This work utilizes the default WordNet package from NLTK and the Energy glossary from the U.S. Energy Information Administration.
4. *Accessing the ontology through owlready2 :* This step involves implementing the code, utilizing owlready2, necessary for manipulating the ontology using Python. This enables querying the ontology to gather all pertinent information from the actors, comprehending their context and, consequently, understanding the meaning of the terms being exchanged.
5. *Implementation:* This step involves implementing the code necessary to convey meaning based on context. This will be accomplished using NLTK, owlready2, and the available glossary at (*EIA Glossary: A*, n.d.).

By doing this, the proposed solution and ontology aim to capture the context of each actor to better understand and convey the meanings of the data they exchange. It should be noted that the context that dictates the meaning is that of the sender, or the actor that sends the exchanged information. As stated, possible difficulties arise from the disconnection between what is sent and what is understood.

### 2.1. Ontology

As seen in Figure 2, the classes and object properties were organized in a way that the context of a given actor, as defined by the role or sector, for example, can be easily captured and used to allocate the correct meaning of what is being exchanged.



**Figure 2:** Class Hierarchy, Data, and Object Properties. The classes are connected by the object properties, representing their relations and which parameters bind them together. Dataproperties represent the lexicon, or how a *word* is written, and the meaning attributed to it.

This hierarchy, as shown in the software Protégé (Research, 2024), represents all classes and related attributes and objects. Their roles, in a broader sense, lie in creating all relations binding an actor to its context, and the meanings of the terms they exchanged based on their context.

### 2.1.1. Actors, Objects and Data Properties

For this work, the ontology will represent two actors, their contexts, and any relevant connections they may have, as shown in Table 1 and 2. Both these actors will exchange information via the proposed ontology and logic, minimizing the risks of miscommunication or data loss due to differing contexts or conventions.

Actor	Context	Explanation
RenewableActor	Renewable Energy Producer	In this scenario, the actor generates renewable energy, specifically solar power.
FossilActor	Fossil Energy Producer	In this scenario, the actor produces fossil fuels by burning coal.

**Table 1:** Actors and Their Respective Context

Element Name	Type	Purpose
actorSector	Object Property	Links actors and their sectors
actorContext	Object Property	Links actors and their context
termHasMeaningByContext	Object Property	Links terms to contexts giving them meaning
termLexicon	Data Property	The lexicon of a given term without meaning
termContentString	Data Property	The description of a term in string

**Table 2:** Object and Data Properties

### 2.1.2. Context

For the purposes of this work, the context of an actor will be defined by the sector in which it operates and the type of energy it produces. However, as noted by (dos Santos et al., 2012), the concept of context is quite vast, and what defines it, or not, may change according to each case.

It should be noted that Python is the language used for this solution, but it is not the only one capable of achieving the desired results. Any packages or libraries with similar functions and objects can be useful, as long as they are able to manipulate ontologies and their contents, process natural language, and parse JSON.

## 3. Experimental Environment and Discussion

### 3.1. Packages

All packages are open source and readily available to be downloaded and imported into any project created using Python. Dictionaries consist of groups of words, meanings, and contexts extracted from web pages referenced in the following Table, which are made available by government institutions.

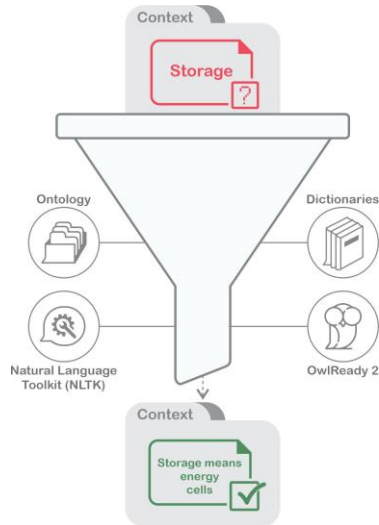
Table 3 shows every package and dictionary name, role, and sources.

Package	Usage	Source
Owl2Ready	Manipulating and reading ontologies, defining context	( <i>OwlReady2 Documentation</i> , n.d.)
Natural Language Toolkit	Manipulating lexicon, terms and possible meanings	( <i>NLTK :: Natural Language Toolkit</i> , n.d.)
Dictionaries	Storing meanings and their related terms	( <i>EIA Glossary: A</i> , n.d.) and (NLTK Project, Accessed: 2024-02-13)

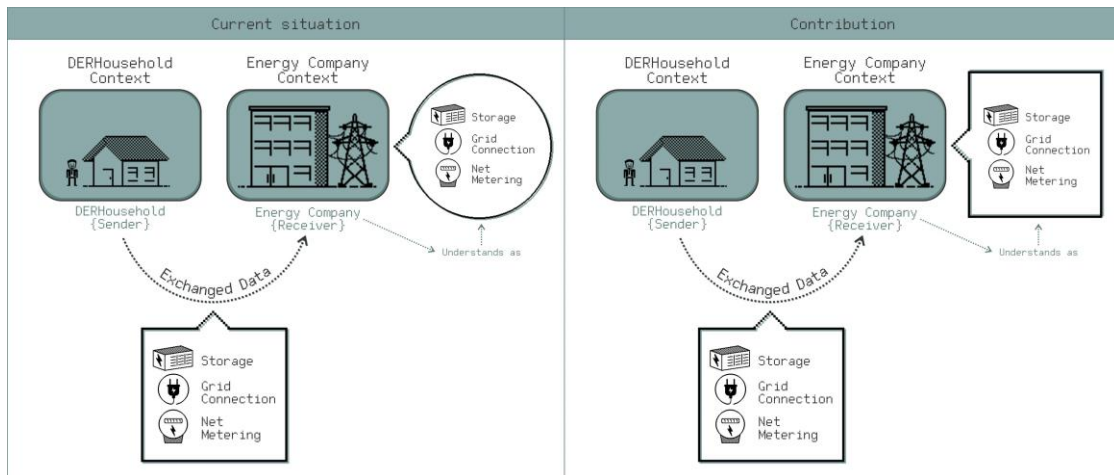
**Table 3:** Packages and their respective uses

These packages work together to find and assign meanings to terms. In this scenario, OwlReady2 is used to manipulate and define data from the ontology. With this, NLTK is used to process the terms so that they can be matched with the most appropriate meaning found in the dictionaries or WordNet available. Figure 3 represents this dynamic, with the proposed solution acting as a *funnel* that receives a term without meaning by context and returns one with it. This *funnel* receives a word, extracted as a

term from the ontology, and runs it against the logic depicted in Figure 5. By doing this, the output is a word with the proper meaning, as per what is defined by the rules implemented by the solution.



**Figure 3:** A term, devoid of meaning defined by its context, is supplied as input to the proposed solution. After processing it against contextual meanings, the output is the same term with the correct one assigned.



**Figure 4:** Two actors attempt to communicate while having different contexts, represented by the speech bubbles. The proposed solution corrects this by having them understand the same meanings.

The topmost *folder*, with the term *storage* written in red, represents a term devoid of meaning. Upon entering the *funnel*, this term is processed by the packages presented in Subsection 3.1. This results in the bottom most folder, now in green, containing the correct meaning according to the sender's context.

### 3.2. Setup and use case

This experiment will be based on a scenario resembling the transition proposed by the German Renewable Energy Sources Act (*Renewable Energy Sources Act (EEG) - Latest Version (EEG 2022)*, n.d.), where there is a gradual shift away from coal-based energy generation towards renewable sources (*Renewable Energy - Federal Ministry of Education and Research (BMWK)*, n.d.). In this scenario, one actor (CoalActor) will represent an energy producer using coal, while another (RenewableActor) will represent a renewable energy producer. They will exchange data that, through the methods proposed in this work, will be understood regardless of the receiver's context. For this purpose, it will be assumed that CoalActor is the sender and RenewableActor is the receiver. The data exchanged, represented by the ontology and manipulated using the packages and techniques described in Section 3.1, will be composed, for testing purposes, of three terms. They are as follows:

Term	Sender's Meaning	Receiver's Meaning	Neutral Meaning ( <i>Cambridge Dictionary</i> , n.d.)
Storage	A place where coal is stored. Generally an openspace.	Batteries or cells used to store energy for future use.	Space used to store something.
Source	The origin of the coal being used for energy production.	The source from which the energy was generated, in this case, photovoltaic panels and windmills.	A place or thing from which something is originated.
Carbon	Data about the carbon found on the coal being used.	Carbon footprint and emissions.	A chemical element that exists in its pure form as diamond or graphite

**Table 4:** Terms and their meanings, based on each actor's context.

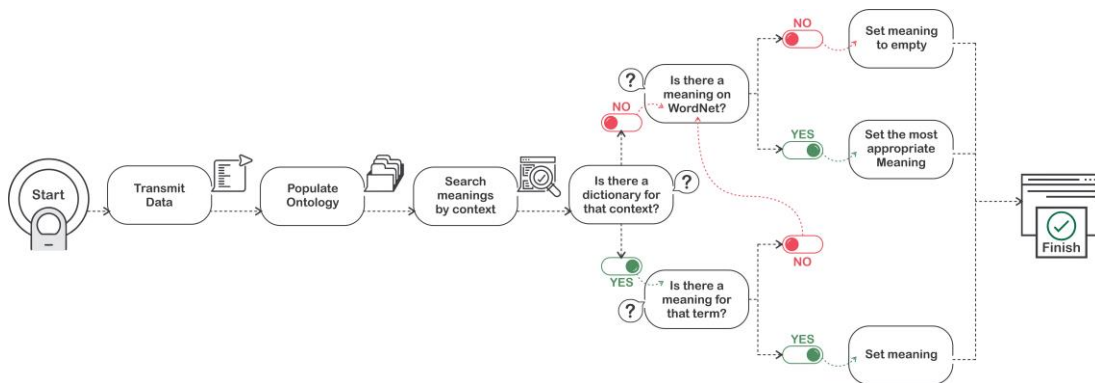
While this example is focused on a reduced amount of words, the same logic could be applied to any terms exchanged that are written in the same way but are interpreted in significantly different manners depending on the context of the receiver.

### 3.3. Meaning Allocation

Following the setup outlined in the previous subsection, the sender will transmit its terms with a meaning that the receiver, upon seeing the message, may not understand. As previously stated, this may occur due to the fact that terms may vary significantly based on the context of who sends the data, whether it be because of geographical reasons, the sector one operates in, the kind of energy it produces, among others.

In order to accomplish this, the proposed logic will search for the context of the actor (based on what was defined in 2.1) and query the dictionaries until a suitable meaning is found. Then, it will append the definition to the term.

The process, as presented, begins with data being exchanged and all terms associated with it being run against all available dictionaries, either the default one created via NLTK or others compiled from other sources. Then, a suitable meaning, if applicable, is added. In case none is applicable, either the meaning is set to empty or whatever message is desired.



**Figure 5:** Process by which the solution defines what meaning is the most appropriate to a given term based on the context of its sender.

### 3.4. Discussion

The proposed solution ensures that RenewableActor, as the receiver, will interpret that the carbon (*data about the carbon found in the coal being used (Cambridge Dictionary, n.d.)*) being transmitted has mineshaft N as its source (*the origin of the coal being used for energy production*). Figure 4 depicts this procedure. In this case, one side of the image represents two actors in different contexts, having difficulties exchanging data, as represented by their "speech bubbles" having different forms. The other side, representing a scenario in which the proposed solution is applied, depicts the exchange occurring in an improved manner.

Based on the results, it's important to highlight that ensuring terms receive their correct meanings, as defined in Subsections 2.1, 2.1.2 and 3.2, led to a reduced likelihood of miscommunication and related problems in the case explored by the experiment. This solution has the potential to mitigate risks associated with questions about the meanings intended by senders and understood by receivers, as well as broader effects originating from changes in context.

Santos et al. (dos Santos et al., 2012) focuses on defining concepts such as context and perception and how they affect the way people collaborate and create. This theory is focused on the realm of collaborative systems. Even if the focus of this author may be on a different domain, the basic ideas remain the same.

Boosheri et al. (Boosheri et al., 2021) introduces the Open Energy Ontology, focusing on how it can be used to promote better data exchange, standardization and knowledge representation in the energy sector. The work does not focus on context and perception. This work extends the proposed ontology by using OEO as basis, proposing classes and objects that are able to capture, represent and assign meaning based on context and perception.

Alawida et al. (Alawida, Mejri, Mehmood, Chikhaoui, & Isaac Abiodun, 2023) explores NLP to be used in applications such as chatbots. These solutions have the potential to search for meanings of words by context, especially when using techniques such as Retrieval Augmented Generation (RAG). It should also be noted that the implementation of RAG is one of the ways in which what is being proposed may evolve.

On that note, this work proposes utilizing NLTK and dictionaries to search for meanings while extending an ontology based on the realities of the energy sector. However, utilizing RAG could be a future improvement.

Under the current premises of what is being proposed, the solution relies heavily on a predetermined dictionary, either built by the combination of others, from different sources, or by using those available by default in packages such as NLTK.

Furthermore, by compiling such dictionaries, future models trained to perform the same task can benefit. Finally, this data is consistent with others readily available for similar use, like those provided by projects such as Red Hen Lab (*Distributed Little Red Hen Lab*, 2024).

## 4. Conclusions and Future Work

This work aimed to propose a simple yet useful solution to the problems arising from the exchange of data from the energy sector, whether it be information or not, between actors inserted in different contexts. By using a combination of ontologies, dictionaries, and the Natural Language Toolkit, any difficulties in understanding the meaning of terms can be solved.

The steps proposed by the methodology, when executed and applied to a use case such as the one provided by this work, result in a scenario in which the potential problems caused by the differences in context and perception between actors can be mitigated.

This is achieved by attaching precise meanings to what is being shared or, at least, providing a general definition. As explored in the subsection 3.4, this could be an interesting tactic to be used in such occasions.

However, there is more that can be done. The use of thesauri, like those compiled by UNESCO, and trained machine models can be seen as a way forward, especially to address cases where a given term does not have a known meaning.

Additionally, the addition of new meanings obtained by this method can enrich existing dictionaries. Finally, the existing code and its rules can also be adapted to encompass other research venues and industries.

A natural evolution of what is being proposed is the implementation of RAG (Lewis et al., 2020). The use of pretrained data, alongside those retrieved from outside sources, can be invaluable in refining the process and ensuring that whatever meaning is assigned will be as close to the intended use, as per context, as possible.

Large Language Models (Gao et al., 2023) (Chen, Lin, Han, & Sun, 2023), used with solutions implementing RAG due to their large number of parameters, are also of interest.

## Acknowledgment

The authors thank CEFET-RJ, INERGE, and the Brazilian research agencies CAPES, CNPq, FAPERJ and INESC P&D for supporting this work.

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# Economic Viability Analysis of Photovoltaic Systems in the Residential Sector in Brazil and Portugal

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## Abstract

The search for renewable energy, driven by high living costs and the attempt to reduce dependence on fossil sources, has led to an increase in photovoltaic solar microgeneration for self-consumption systems. This study compares the economic viability of these systems in Brazil and Portugal, considering legislation, energy compensation, and solar metric conditions. The analysis includes sizing installations, projections in PV\*SOL software, and financial comparison. The results obtained show that, although Portugal has a more advantageous initial investment, the financial balance is superior in Brazil, due to legislative differences and surplus energy selling prices.

## 1. Introduction

To mitigate problems related to the excess injection of photovoltaic solar energy into the electrical grid, both in Brazil and Portugal, the laws governing electricity compensation are continuously being adjusted by the responsible authorities. From the recent changes in the legislation regarding the sale of surplus energy in both countries, the impacts are mainly evaluated in terms of the accumulated financial balance. In Brazil, Law 14.300/2022 (DIÁRIO OFICIAL DA UNIÃO, 2022) aims to tax the compensation of surplus energy. In Portugal, Decree-Law No. 15/2022 (Diário da República, 2022) favors self-consumption with a low tariff for the sale of surpluses. In this regard, two equivalent photovoltaic systems were designed, one in each mentioned country, with the objective of comparing economic viability in each scenario. The methodology used to obtain the results stems from simulations conducted in the PV\*SOL software, whose returned graphs allow for a more accurate analysis.

## 2. Legislation

In the Brazilian scenario, for self-consumption systems, the purchase and sale of energy are provided by the same energy supplier company, since within the captive market there are no other options besides the one predetermined by the installation location. In the country, Normative Resolution (REN) 482 (ANEEL, 2012) was revoked with the enforcement of Law 14.300/2022: The Legal Framework for Distributed Generation (DG), associated with Normative Resolution 1059 (AGÊNCIA NACIONAL DE ENERGIA ELÉTRICA – ANEEL, 2023).

Under REN 482, the sale of surplus energy was more advantageous for the consumer, as the kWh selling price was identical to the consumption price, according to the utility's tariff. However, Law 14,300 DG proposes a progressive tariff system on part of the energy injected into the grid, related to Fio B (which are the costs linked to the use of the local utility's distribution network infrastructure to homes, businesses, industries, and rural properties) of the Tariff for the Use of Distribution System Services (TUSD). This taxation only applies to the amount of energy injected into the electrical grid, encouraging the optimization of systems for self-consumption, since the financial return is tied to the generation of system surplus (Marques, 2022).

Portugal's legislation differs due to the availability of energy having a more decentralized character, as a large part of consumers have their tariffs linked to the free energy market, rather than the regulated captive market. As

a free market, the kWh price varies according to each available supplier, both for consumption and for sale, not being predetermined by the installation location. Moreover, the consumption and sale companies are considered distinct entities, with consumption present in the distribution sphere and sale in the energy generation sphere.

The EU Directive 2019/944 and the EU Directive 2018/2001 were transposed by the current legislation of Decree-Law (DL) No. 15/2022, effective since January 14, 2022. This DL establishes the organization and functioning of the National Electric System (SEN), including microgeneration and self-consumption systems. The DL determines how to interact with the energy supplier and connect to the grid. Previously, the produced energy was for consumption and the surplus was sent to the grid without compensation. Now, if desirable, the Self-Consumption Production Unit (UPAC) must request a Producer Delivery Point Code (CPE) from the energy distributor. This makes it possible to choose to sell surplus energy. (Diário da República, 2022).

### 3. Methodology

The methodology was divided into four main stages, the first being the study of the current legislation in each country, focusing on the surplus sale tariffs, as presented in section 2 of this article. Subsequently, the pre-project as the second stage, in which the necessary power to meet the energy demands of a residence is stipulated. Based on this, real consumption values of a residence located in the mountainous region of Rio de Janeiro, Brazil, were acquired, resulting in a need for 4000 kWh of annual self-consumption. This resulted in a stipulated power of 3,300 Wp, which will be a baseline value for the choice of system equipment to be installed, depending on the availability in each country.

To obtain this value, through market research in both scenarios, the equipment with the best cost-benefit was selected. In Brazil, for the mentioned residence, eight 445 Wp photovoltaic modules from Canadian Solar were used, associated with two 1.6 kW micro-inverters from DEYE, resulting in an installed power of 3560 Wp. In Portugal, 550 Wp modules from Axitec were used, with a 3.0 kW inverter from GoodWe, the most viable materials at the moment, resulting in an installed power of 3300 Wp. These technical data are reflected in Table 1.

Characteristics	Brazil	Portugal
DC Peak Power (Wp)	3560	3300
Number of Photovoltaic Modules	8	6
Power per Photovoltaic Module (Wp)	445	550
Inclination Angle of Photovoltaic Modules (°)	23	35
Azimuth Angle of Photovoltaic Modules (°)	0	180
Power per Inverter (W)	1600	3000
Number of Micro-Inverters/Inverters	2	1
AC Nominal Power (W)	3200	3000
Estimated Annual Production (kWh)	4672	4818
Self-consumption (kWh)	4000	4000
Injection of Surplus into the Grid (kWh)	672	818
Estimated Losses due to Cabling (%)	0.98	0.98

**Table 4:** Technical Data Summary

For the third stage, aiming at the appropriation of the material, it is necessary to investigate the economic scenario of each country, with the respective difficulties linked to purchasing power, minimum wage, disparity between local currencies, and the price of the photovoltaic kit. The Real, the currency used in Brazil, according to The Economist, was devalued by 17.3% (The Economist, 2024) in relation to the Euro (currency used in Portugal) in June 2023. The exchange rate used was from that time, where the value of the euro was 5.20 reais, in July 2023 (The Economist, 2024) In this way, the values were converted to allow comparison in euros.

The price of the photovoltaic kit for the stipulated power, converting the values to euros, is 1698.00 € and 1268.00 € for Brazil and Portugal, respectively (values from June 2023). It is noteworthy that the minimum wage in Portugal is approximately 820.00 € (value corresponding to 14 annual salaries) (Portugal.GOV.PT, 2023), while in Brazil the approximate value is 260.00 € (value corresponding to 13 annual salaries) (Máximo, 2024).

The average inflation rate presented at the date of this study is 4.3% in Portugal 3% (Instituto Nacional de Estatística - INE, 2024) and 4.7% in Brazil (Portal Solar, 2024) in 2023. Injection and energy tariffs also show inflation, with the inflation value for electricity being 7.7% in the state of Rio de Janeiro (Brazil) in 2023 (Portal Solar, 2024). In Portugal, the general inflation rate of 4.3% was used for both tariffs (Instituto Nacional de Estatística - INE, 2024).

It should be noted that, evaluating the inflation rates of previous years, the inflation rate for 2023 is atypical, being a value higher than the average Portuguese standard. This is due to particularities, such as the war in Ukraine.

Still in this stage, the purchase and sale values of kWh in the two countries stand out. The purchase values are 0.200 euros (edp, 2024) and 0.250 euros (ENEL 2024, 2024) for kWh consumed in Bragança (Portugal) and Rio de Janeiro (Brazil), respectively. These values are from January 2024. In Brazil, the sale value of the surplus varies according to progressive taxation (Table 3), with the value being 0.231 euros in 2024 (ENEL 2024, 2024), based on the utility company Enel. In Portugal, the sale value was based on the contract proposed by EZU, one of the companies buying surplus kWh in the Portuguese scenario, presenting the value of 0.06 € for the sale of 1 kWh (EZU Energia, 2024). These economic viability data can be reflected in Table 2.

Attribute	Brazil	Portugal
Cost of Photovoltaic Kit (€)	1698.00	1268.00
Minimum Wage (€)	880.00	260.00
Average Inflation (%)	4.7%	4.3%
Electricity Inflation (%)	7.7%	4.3%
Energy Purchase Price (€)	0.250	0.200
Energy Selling Price (€)	0.231	0.060

**Table 2:** Economic Data Summary

Year	Rate	Selling Price kWh (€)
2023	15%	0.241
2024	30%	0.231
2025	45%	0.221
2026	60%	0.210
2027	75%	0.200
2028-2030	90%	0.190
2031-2050	100%	0.184

**Table 3:** Resumo da taxaço progressiva

Table 3 reflects the update of Brazilian legislation, depicting the progressive taxation system on part of the energy injected into the grid, related to Fio B (which are the costs linked to the use of the local utility's distribution network infrastructure to homes, businesses, industries, and rural properties) of the Tariff for the Use of Distribution System Services (TUSD).

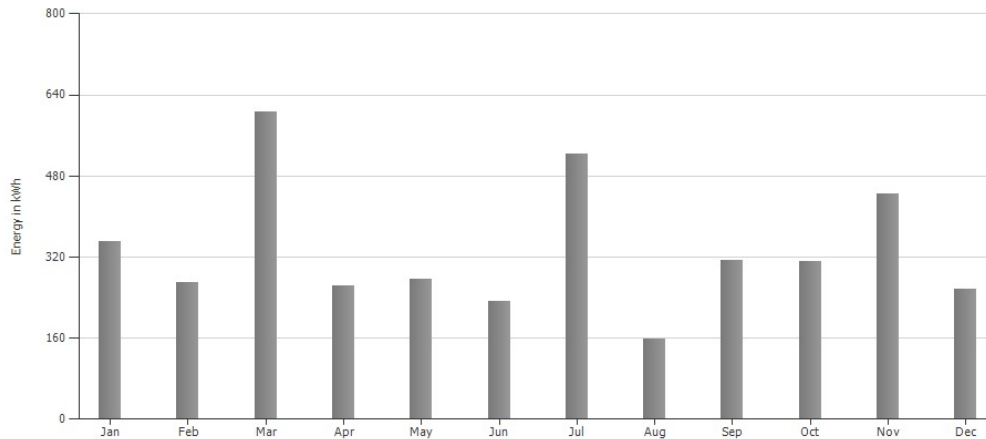
This taxation only applies to the amount of energy injected into the electrical grid, encouraging the optimization of systems for self-consumption. The rates are fixed and defined by Law 14,300 DG for each year of operation of the photovoltaic system. The selling price values are the result of applying these rates to the updated TUSD Fio B values, reflecting the decrease in the selling price over the years due to inflation rate adjustments.

For the fourth stage, the previously determined technical and financial values were entered into the PV\*SOL software to generate results for the energy produced over the years of operation of the photovoltaic system. In this stage, it is indicated whether the system will be grid-connected or not, and the consumption is evaluated, among other options. In both scenarios, the systems are On-Grid, connected to the public electrical grid. This is to assess the financial return with the surplus injected into the electrical grid.

Regarding the climatic data of irradiation, when choosing the installation location, PV\*SOL itself acquires the values through its meteorological database, Meteororm 8.1. Then, the data related to the type of supply by the

utility company responsible for the location in question are entered. In this way, mainly the voltage levels and the number of phases of the input standard are indicated.

If the system is for consumption (self-consumption), it is necessary to provide the values in kWh present in the historical energy consumption of the installation in question. By entering them, the software generates a load diagram corresponding to the energy consumption values for each month throughout the year, in kWh. These values will be used for the calculation of surplus sales and can be observed in Figure 1.



**Figure 1:** Annual Load Diagram Chart, by Month, Generated by PV\*SOL

Following the use of the software, the second step consists of 3D modeling. In this stage, the residences were designed by prioritizing only the roof inclination consistent with the optimal inclination angles of the photovoltaic modules in each scenario. After creating the 3D model of the roof, the photovoltaic modules are allocated and connected to the inverters.

From this step, the respective inverters are inserted. In this stage, there is also the cabling between the modules and inverters, which can be done automatically by the software or manually by the designer. Next, there are the cable and wiring losses. However, for this analysis, a fixed value of 0.98% losses is used, which is a theoretical standard value.

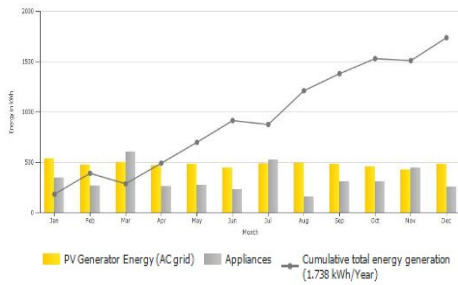
The final stage of the software consists of the rates and tariffs of the energy supply companies. PV\*SOL provides some data from a few utility companies, but if the installation location has another utility not registered in the system, there is the option to add a new utility, providing the kWh sale values, associated with the annual inflation values. Thus, the necessary values were inserted for both projects, according to the values previously presented in this work.

Finally, the data generated in both simulations is analyzed, comparing the obtained graphs of energy and financial data for the systems designed in Brazil and Portugal.

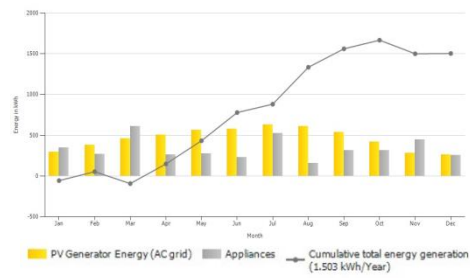
## 4. Results

According to the presented data, through the respective graphs generated by the PV\*SOL software, relevant results such as the financial balance and the forecast of financial return are obtained. Thus, based on this information generated by the reports, comparisons can be made to identify in which country it is more economically viable to install photovoltaic systems in residences.

The energy balance (Figure 2 and 3) indicates an increase, as generation exceeded consumption during 9 out of the 12 months of the year in both cases, indicating that the system is correctly sized. As shown, the line represents the accumulated surplus over 1 year. It is noted that there is a surplus in production of more than 1500 kWh/year for both, which will highlight the differences between the financial compensation laws.

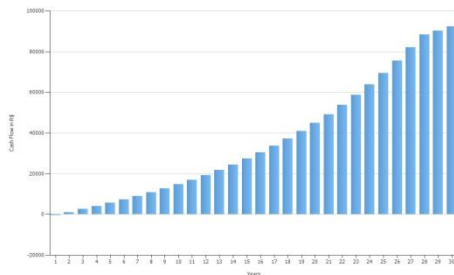


**Figure 2:** Brazilian energy balance

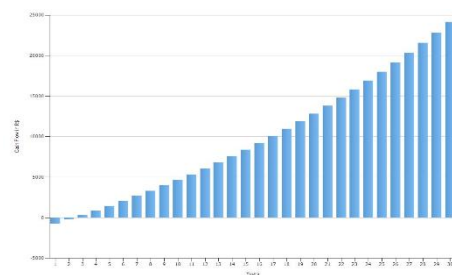


**Figure 3:** Portuguese energy balance

Related to this, there is the graph of the accumulated financial balance (Figure 4 and 5). At the beginning of the sizing, there is naturally a cost due to the initial investment for the project. However, with the reduction in the amount charged on the energy bill, combined with the eventual sale of the surplus, the project tends to show a financial return gradually over the years.



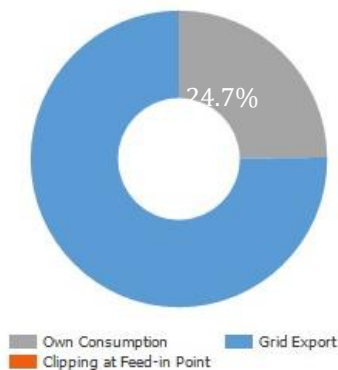
**Figure 4:** Accumulated financial balance in Brazil



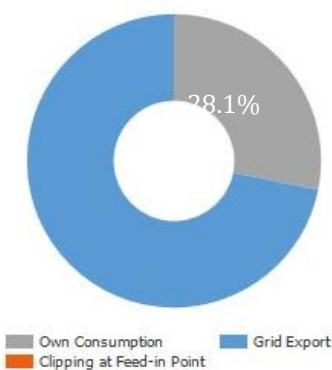
**Figure 5:** Accumulated financial balance in Portugal

In the first case, the financial return starts from the 3rd year after installation. As the tariff for selling the surplus is low, the flow at the end of 30 years approaches 25,000 euros. In the second case, the return already happens in the second year after installation, with an accumulation of around 90,000 euros over 30 years, clearly showing how, despite the change in the new compensation law, it is still extremely advantageous to sell the surplus in the Brazilian scenario compared to the Portuguese scenario.

It is noted that, in the Portuguese scenario, the graph follows almost a linear growth, using the premise of a fixed surplus sale rate and relatively low inflation. However, in Brazil, the flow tends to stagnate at the end of the years when taxation is higher and at a constant value. It is worth mentioning that, when simulating various scenarios in the software, varying the year of installation of residential microgeneration, the financial balance value is significantly lower the later the installation, as the stagnation of sale values occurs more quickly. However, within this scenario, financially, the Brazilian legislation is still more advantageous than the Portuguese one in terms of financial compensation related to the sale of surplus electricity.



**Figure 6:** Brazilian utilization factor



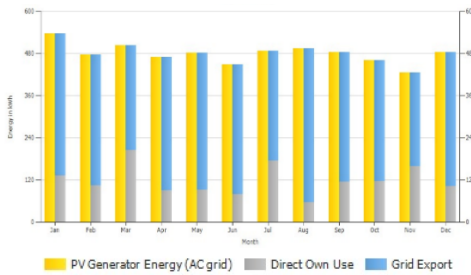
**Figure 7:** Portuguese utilization factor

Another analysis is the utilization of the generated energy to evaluate how much of the photovoltaic generation is used directly and how much is injected into the electrical grid. Since these are two residences, the period of highest generation usually does not coincide with the period when the residents are using the electricity. Thus, a significant portion of the generation is injected into the grid.

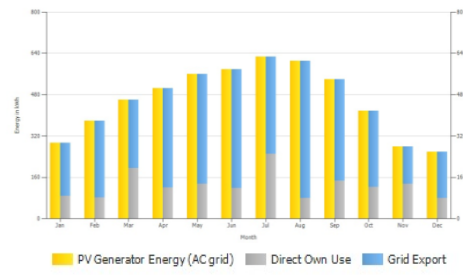
The utilization factor is directly linked to the load curve of each case. In the Bragança simulation, the software does not have a specific load curve for the city. Therefore, a generic load curve with late afternoon peaks was used. This curve was chosen due to its similarity to the load curve of Rio de Janeiro and because it is typically the period when most of the population is at home and using the electrical grid.

Again, the software evaluated the system's direct self-consumption and the consumption covered by the photovoltaic system. In Bragança (Figure 7), 28.1% is direct self-consumption, a value within the expected range for this type of installation.

In the Teresópolis simulation, the residential load curve of ENEL in the state of Rio de Janeiro was used. This load curve is a specific curve based on energy use in that region. Thus, the software evaluates the system's direct self-consumption and the consumption covered by the photovoltaic system, in which, in the Teresópolis project (Figure 6), 24.7% is direct self-consumption.



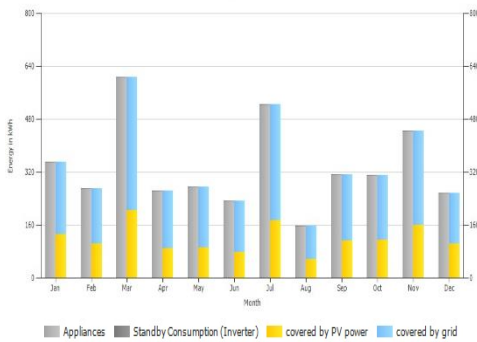
**Figure 8:** Utilization photovoltaic energy in Brazil



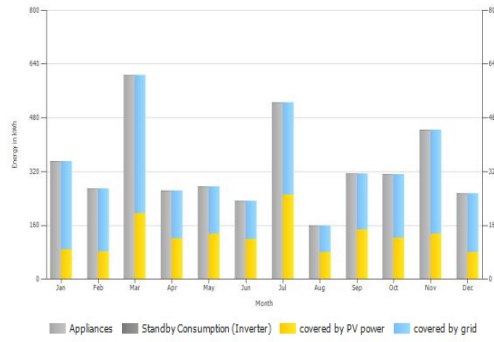
**Figure 9:** Utilization of Photovoltaic Energy in Portugal

Figures 8 and 9 indicate the photovoltaic generation and the destination of the generated energy. The gray bars indicate the direct self-consumption of the production, while the blue bars indicate what is injected into the electrical grid. It is noted that, as justified in the paragraph above, a significant portion is injected. Since the sale of the surplus is not very advantageous in the Portuguese scenario, it is understood that the use of zero-grid systems or the use of hybrid systems with batteries is more advantageous in this aspect. It is worth highlighting that the disadvantage is related to the sale of the surplus, as the financial return on this investment is still advantageous considering the reduction in electricity bill values.

However, in the Brazilian scenario, since the sale of the surplus is still extremely advantageous, both direct consumption and injection into the grid are beneficial, although the injection is greater than the direct self-consumption.



**Figure 10:** Brazilian consumption coverage



**Figure 11:** Portuguese consumption coverage

Still following the same line, we obtain the consumption coverage graphs, which represent, within the consumption inserted throughout the year, the proportion of how much of the consumption is covered by the photovoltaic system and how much is covered by the local electrical grid.

It is noted that, in Teresópolis (Figure 10), most of the consumption comes from the use of the electrical grid, being dominant in all months of the year. In Bragança (Figure 11), in some months of the year, most of the consumption comes from the generated photovoltaic energy, a scenario that is most suitable when sizing an On-Grid photovoltaic system. This difference between the two scenarios is due to the load curve established in each location.

It is worth mentioning that although production is higher than consumption for most of the year, this does not prevent consumption from the electrical grid, as often the use of energy in a residence is mainly during periods when there is no photovoltaic energy generation, resulting in an energy deficit.

## 5. Conclusions

The results highlight that the differences in financial compensation laws reflect almost immediate returns in Brazil for residential photovoltaic systems, despite the challenge of purchasing power. On the other hand, in Portugal, the main advantage lies in the initial accessibility of the systems, provided by the low cost in relation to the minimum wage, although the sale of excess energy is not as profitable due to the low selling prices per kWh. In conclusion, while the investment in self-consumption is more accessible in Portugal, the financial return is faster in Brazil, despite the initial economic challenges for both countries.

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# The Wind Energy Market and the Institutional Influences of Non-Market Strategy in the Northeast Region – A Case Study on Enel Green Power.

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## Abstract

The Northeast region of Brazil has stood out in the development of wind energy, attracting investments from multinational companies like Enel Green Power. This case study analyzes the company's operations in the region, considering both the economic and social benefits, as well as the negative environmental impacts resulting from the expansion of wind farms. Enel Green Power, a subsidiary of the Italian group Enel, is one of the main developers of wind projects in the Northeast, with projects in states such as Bahia, Piauí, Rio Grande do Norte, and Ceará. The company faces challenges related to adapting to local environmental regulations, community engagement, and transmission infrastructure. Additionally, adverse climatic conditions and competition in the wind market are significant obstacles. The study proposes non-market strategies for Enel Green Power, aligning its interests with those of local institutions and stakeholders. The main strategies include: Community Engagement and Environmental Education: Implementing educational programs and volunteer initiatives to build trust and awareness about wind energy. Transparency and Corporate Social Responsibility: Publishing annual sustainability reports and creating transparent communication channels to demonstrate commitment to responsible environmental and social practices. Strategic Partnerships with NGOs and Local Institutions: Collaborating with NGOs and local institutions to mitigate negative impacts and promote sustainable development. These strategies are essential for addressing socio-environmental challenges and strengthening Enel Green Power's commitment to sustainability and the well-being of the communities in which it operates.

Keywords: wind energy, regulations, interest groups, non-market.

## 1. Introduction

The Northeast region of Brazil has consolidated itself as a strategic hub in the development of wind energy, thanks to its favorable climatic conditions and the availability of vast areas for the installation of wind farms. This promising context has driven significant investments and placed the region at the forefront of the renewable energy sector in the country, led by major multinational companies operating in the Northeast, such as Iberdrola (Neoenergia), Votalia, Casa dos Ventos, and Enel Green Power. However, the rapid growth of this market also brings to light a series of socio-environmental issues that require careful and detailed analysis.

Furthermore, the growth and potential of the wind energy market in the Northeast will be examined, due to its ideal climatic conditions, such as constant and intense winds, and the availability of large areas for the installation of wind farms, which attracted approximately \$4.5 billion in investments in the wind sector, with a significant portion directed to the Northeast. The socio-environmental impacts and positive aspects related to the wind energy market in the Northeast will be highlighted, emphasizing how the interaction between economic development and environmental preservation can be managed sustainably to promote regional growth and mitigate climate change. The social impacts, including land conflicts and changes in the local landscape, as well as environmental impacts such as wildlife mortality and alteration of natural habitats, will also be addressed. The Northeast region of Brazil is one of the most important for wind energy production, thanks to its excellent wind resources. Various companies are operating in the region, contributing to significant growth in this sector. However, many studies have investigated a limited selection of non-market institutions in relation to the non-market behavior of these companies. Multinationals must deal with various types of institutions and their

pressures in the non-market context simultaneously. How they manage the influences of these institutions depends on the perceived power and formal and informal obligations of the institutions.

The concept of non-market strategy refers to the activities that organizations engage in outside the traditional market of buying and selling goods and services. These strategies aim to influence the external environment of the company, shaping government policies, regulations, and public opinion (Baron, D. P., 1995, p. 47-65).

Non-market institutional pressures consist of various factors. Our understanding of the composition of the drivers and the perceived power of non-market institutions in a specific context, as well as the responses of multinational companies, remains limited (Hiatt et al., 2015).

This case study will analyze the Italian company Enel Green Power, which seeks to comprehensively explore the wind energy market in the Northeast, highlighting both the economic and social benefits and the negative environmental impacts associated with this expansion. In the current competitive business landscape, it has become essential for most multinational enterprises (MNEs) to focus not only on relationships with market actors but also with non-market institutions: political, regulatory, and standard-setting institutions, as well as social institutions like the media and interest groups (Hillman et al., 2004; Mellahi et al., 2016). The analysis encompasses economic aspects such as job creation and attracting investments, while also considering challenges related to infrastructure and public policies. It will present the negative impacts that the installation and operation of wind farms can generate. The economic, social, and environmental aspects that influence and are influenced by the growth of this sector will be addressed, analyzing the perceived formal and informal drivers of certain classes of non-market institutional influences and the resulting relationships between the classes of pressures and the responses of Enel Green Power.

Existing literature on the factors driving institutional pressures has largely developed from two main perspectives: the institutional perspective and corporate political strategy. Different perspectives represent the next logical step in advancing non-market strategy research.

The choice of Enel Green Power for this research stems from the relevance and importance it plays in society and the market, given its investments and socio-economic impacts. This favorable scenario has attracted significant investments and placed the region at the forefront of the renewable energy sector in Brazil. The wind potential of the Northeast region of Brazil is vast and still underexplored, representing a significant opportunity for future expansion. The Northeast has the highest installed capacity of wind energy in Brazil, with states like Rio Grande do Norte, Bahia, and Ceará leading in this sector (ABEEólica, 2021).

## 2. Growth and potential of the wind energy market in northeast brazil

The Northeast region of Brazil has emerged as a crucial center for the development of wind energy in the country, due to its ideal climatic conditions, such as constant and intense winds, and the availability of large areas for the installation of wind farms. This favorable scenario has attracted significant investments and placed the region at the forefront of the renewable energy sector in Brazil. The wind potential in Northeast Brazil is vast and still underexplored, representing a significant opportunity for future expansion. The Northeast has the highest installed capacity of wind energy in Brazil, with states like Rio Grande do Norte, Bahia, and Ceará leading in this sector (ABEEólica, 2021).

Technological advances have improved turbine efficiency and reduced costs, making wind energy a competitive option compared to traditional energy sources. The accelerated growth of wind energy in the Northeast has brought numerous economic benefits, but also challenges, particularly related to infrastructure and planning. The sector is highly dependent on government incentive policies. Any change or instability in these policies can negatively affect investments and market growth. The installed capacity of wind energy in the Northeast has grown significantly over the years. According to data from the National Electric Energy Agency (ANEEL), the Northeast leads with approximately 83% of Brazil's installed wind energy capacity, experiencing exponential growth in recent decades. States like Rio Grande do Norte, Bahia, and Ceará concentrate about 90% of Brazil's installed wind energy capacity. In 2021, wind energy accounted for approximately 10% of Brazil's electricity matrix, with a trend of continuous growth (ANEEL, 2021).

Despite this growth, energy transmission infrastructure still requires improvements to prevent waste and ensure efficient distribution. The continuity and enhancement of incentive policies are crucial for maintaining the sector's growth pace.

Investments in wind energy in the region have been robust. In 2020, Brazil attracted approximately \$4.5 billion

in investments in the wind sector, a significant portion directed to the Northeast. These investments not only boost energy generation capacity but also promote regional economic development. The renewable energy incentive policy, including wind energy, has been crucial in attracting investments and driving sector growth in the Northeast (MME, 2021).

The Northeast region has been attractive for foreign investments in the wind energy sector due to its favorable climatic conditions and stable regulatory environment (EPE, 2021).

The wind energy market in Northeast Brazil presents enormous growth potential, driven by natural conditions and favorable policies. However, the expansion of this market must be accompanied by careful management of socio-environmental impacts. Developing a balanced strategy that prioritizes sustainability and community engagement will be essential to ensure that wind energy growth contributes to both economic progress and environmental preservation in the Northeast.

### 3. Socio-environmental impacts and their aspects on local development

The Northeast region, known for its favorable natural conditions—such as constant, high-intensity, and low-turbulence winds—provides an ideal environment for wind energy generation. States like Rio Grande do Norte, Bahia, and Ceará stand out as major wind energy producers in Brazil, with significant installed capacity growth in recent years.

The construction and operation of wind farms generate thousands of direct and indirect jobs, contributing to reducing unemployment and local economic development. It is estimated that the wind sector has generated over 200,000 direct and indirect jobs in the Northeast to date (ABEEólica, 2021).

Alongside job creation, investments in wind energy boost local economic development through infrastructure improvements, increased tax revenues, and strengthening regional economies. The establishment of wind farms has significantly contributed to the economic development of states like Bahia, Rio Grande do Norte, and Ceará, generating jobs and increasing tax revenue (CNI, 2020).

Wind energy is a clean, renewable energy source that significantly contributes to reducing greenhouse gas emissions. This helps Brazil meet its climate goals under the Paris Agreement and combat climate change. The presence of large wind turbines alters the natural and rural landscape, which can negatively impact tourism and the well-being of local communities. In some areas, the installation of wind farms may negatively affect cultural heritage and local traditions, leading to a loss of cultural identity and traditional practices.

The installation of wind farms often involves land expropriation, which can lead to conflicts with local communities and small landowners. These conflicts can result in legal disputes and social tensions. The presence of large wind turbines alters the natural and rural landscape, which can negatively impact tourism and local community well-being. Furthermore, it may affect cultural heritage and local traditions, leading to a loss of cultural identity and traditional practices.

Wind turbines pose a risk to aerial fauna, particularly birds and bats, which can be injured or killed by moving blades. The construction of wind farms may also lead to the modification or destruction of natural habitats, affecting local flora and fauna. The operation of turbines generates noise and vibrations that can impact terrestrial and aquatic fauna, as well as affect the quality of life of people living near wind farms. Due to the significant variation in individual tolerance levels to noise, there is no completely satisfactory way to measure its subjective effects or the corresponding reactions of annoyance and dissatisfaction (PINTO, 2013).

Turbine noise can cause harmful health symptoms, such as: (a) sleep disturbances; (b) ear pressure; (c) nausea; (d) vomiting; (e) dizziness; (f) irritability; (g) concentration problems; (h) memory failure. Currently, modern projects have been developed with proposals to possibly reduce this type of discomfort to people's health.

To ensure the long-term sustainability of wind energy development, it is crucial to implement sustainable planning practices and conduct rigorous environmental impact studies. This includes careful site selection, adopting mitigation measures to protect local fauna, and involving local communities in the decision-making process. The installation of wind farms can affect local fauna, especially birds and bats. Mitigation measures, such as careful site selection, are essential. The construction of wind farms occupies large areas, which can lead to the modification of natural habitats and the use of agricultural land.

- Waste Management: The production and eventual replacement of turbines generate waste,

including non-recyclable materials, that need to be managed sustainably to avoid long-term environmental impacts.

- **Turbine Life Cycle:** The construction, operation, and decommissioning of turbines have environmental impacts. It is important to consider the entire life cycle of the turbines to minimize these impacts, from raw material extraction to final disposal. In pursuit of clean energy production, opting for wind energy is an excellent alternative for sustainability. The Northeast region of Brazil stands out nationally for its installed wind energy capacity, driven by favorable climatic conditions and significant investments. According to the National Electric Energy Agency (ANEEL), by 2021, the Northeast had approximately 17.1 GW of installed wind energy capacity, representing about 83% of the national total (ANEEL, 2021). Wind energy plays a crucial role in diversifying the Brazilian energy matrix, especially in the Northeast, where wind conditions are favorable and the generation potential is significant (ABEEólica, 2021).

The states in Northeast Brazil most affected by the wind energy market are those with the highest wind potential and, consequently, the greatest concentration of wind farms. Here are some of the most impacted states:

- **Bahia:** Leads in installed wind energy capacity in Brazil, with wind farms distributed along its coastline and interior. The installed capacity exceeds 5,600 MW (ABEEólica, 2021). The installation of wind farms may result in the fragmentation of natural habitats, affecting local biodiversity and its ecological interactions (WWF, 2019). Wind turbines can generate noise that interferes with local fauna, affecting migratory routes and animal behavior (EPE, 2021). The modification of the landscape due to infrastructure installation, such as wind towers, may visually alter natural areas and affect local tourism (ANEEL, 2020).
- **Rio Grande do Norte:** Also has significant installed wind energy capacity, with farms concentrated mainly in the coastal region. The installed capacity in the state exceeds 5,000 MW (ABEEólica, 2021). Wind turbines may pose a risk to birds and bats that may collide with the blades. This could impact local populations of species, especially migratory ones. Although wind farms can bring investments and temporary jobs to the region, the economic benefits are not equally distributed. There may be a concentration of wealth in the hands of a few landowners and investors while the local population faces ongoing economic challenges (CNI, 2020).
- **Ceará:** Shows significant growth in the wind sector, with wind farms installed in various regions of the state. The installed capacity significantly contributes to the regional energy matrix (ABEEólica, 2021). The installation of wind farms can generate land use conflicts, mainly in areas used for agriculture, livestock, and fishing. These conflicts can lead to the displacement of local populations and the loss of traditional lands (MME, 2021). The local economy may undergo changes with the introduction of wind farms. Traditional activities, such as artisanal fishing, may be negatively affected due to changes in land use and the availability of natural resources (EIA, 2021).

In this context, it is evident that the wind energy market and its socio-environmental impacts, both positive and negative, warrant further study to avoid adversely affecting local development in Northeast Brazil.

Although wind energy brings many economic and environmental benefits, such as reducing greenhouse gas emissions and diversifying the energy matrix, it is essential to address and mitigate the negative socio-environmental impacts. Implementing sustainable planning practices, conducting rigorous environmental impact studies, and involving local communities in decision-making are fundamental steps to ensure that the development of wind energy in Northeast Brazil is balanced and beneficial for all involved. The actions of wind energy companies in the Northeast.

**Table 1** - Companies Operating in the Northeast Region

Company	Country of Origin	States of Operation	Financial Setbacks	Environmental Setbacks
Enel Green Power	Italy	Piauí, Bahia, RioGrande do Norte, Pernambuco	Infrastructure challenges and bureaucracy, as well as potential project delays.	Impacts on local fauna and flora, especially during the construction of wind farms.
Casa dos Ventos	Brazil	Ceará, Rio Grande do Norte, Piauí, Bahia, Pernambuco	High implementation and maintenance costs of the parks.	Conflicts with local communities, deforestation, and land-use changes.
Iberdrola (Neoenergia)	Spain	Bahia, Paraíba, RioGrande do Norte, Pernambuco, Piauí	Regulatory challenges and the need for integration with the electrical grid.	Visual and noise impact, and potential damage to local ecosystems.
Voltaia	France	Rio Grande do Norte, Bahia	High infrastructure and technological adaptation costs.	Changes to marine and terrestrial habitats near the projects.

Source: Prepared by the authors

## 4. Enel Green Power

Enel Green Power is a subsidiary of the Italian group Enel, one of the largest energy companies in the world. The company began operations in Brazil in the 2000s, initially focusing on renewable energy, including wind power in the Northeast region. It quickly established itself as one of the leading developers of wind projects in the area. Over the years, Enel Green Power expanded its installed capacity by developing several wind farms in states such as Bahia, Piauí, Rio Grande do Norte, and Ceará. These projects have helped diversify the local energy matrix and increase the share of renewable sources in electricity generation.

The company not only built wind farms but also invested in transmission infrastructure to connect its projects to the national grid, overcoming logistical challenges and network access issues. Environmental and energy regulations can be complex and vary from state to state in Brazil. Adapting to local environmental licensing requirements and obtaining the necessary authorizations for the construction of wind farms has been an ongoing challenge. Organizations like the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA) and state environmental secretariats regulate the licensing of wind projects. Enel Green Power has faced challenges in complying with these environmental requirements, including the mandatory completion of Environmental Impact Studies (EIA) and the creation of Environmental Compensation Programs to mitigate impacts on local fauna and flora.

The lack of adequate transmission infrastructure has posed significant difficulties. Enel Green Power encountered challenges connecting its wind farms to the national grid, which can affect the economic viability of the projects. Despite the natural advantages of the Northeast region for wind energy, adverse weather conditions, such as irregular or extreme winds, can impact energy production and operational efficiency.

The company has had to address community engagement issues, including the challenge of gaining support from local communities and mitigating environmental concerns related to impacts on local fauna and flora. The wind market is highly competitive, with several companies seeking a share of the sector. Enel Green Power has had to contend with competition while maintaining its position as a market leader through technological innovation and operational efficiency.

Changes in environmental and energy regulations can directly affect Enel Green Power's operations. This includes stricter environmental licensing requirements, tougher emissions standards, and policies for subsidies and tax incentives for renewable energy. Political decisions regarding energy tariffs, renewable energy auctions,

project concessions, and other governmental policies can impact the economic viability of Enel Green Power's projects in the Northeast region.

Pressures from civil society and environmental groups for sustainable and responsible practices can influence the company's reputation and its relationships with local communities. National and international economic and political instability can affect project financing, access to credit, and investor confidence in the renewableenergy sector.

The company was fined approximately 25 million reais, which would be allocated to actions for the recovery and mitigation of damage caused to affected communities (SEMAR, 2021b). According to the Enel Brazil Sustainability Annual Report (2021), the company did not disclose any social projects on its digital platforms (except for a playground in Araras mentioned in its 2021 sustainability report) or measures to mitigate damages caused.

According to official documents collected and field research, the damage to the rural community, its lands, animals, soil, and vegetation has been severe, and the company's actions have not yielded positive returns compared to what has been lost by affected communities and the environment. It is noted that no direct actions have been taken concerning the Gurgueia River, which is significantly silted.

## 5. Analysis of enel green power's results

After analyzing the challenges faced by Enel Green Power in the solar energy sector and considering possible non-market strategies that the company may adopt, the following fundamental approaches are identified:

### 5.1 Community Engagement and Environmental Education Strategy:

The goal is to build a trusting relationship with local communities and raise awareness about the socio-environmental benefits of wind energy. This can be implemented by introducing programs in schools that address the impact of renewable energy, as well as lectures and workshops on this often-overlooked topic and its contribution to local sustainability. Encouraging volunteer initiatives among Enel Green Power employees to support local community projects is also recommended. As a result, the company is expected to be viewed positively, reducing conflicts and improving acceptance of its projects. These strategies can help create a more stable and harmonious operational environment for Enel Green Power in the Northeastern wind market.

### 5.2 Transparency and Corporate Social Responsibility Strategy:

The goal is to make the company increasingly transparent and demonstrate that it cares about ethical and responsible business practices. This can be implemented through various means: publishing annual sustainability reports that include environmental and social practices not only locally but throughout the Northeast; creating communication channels for feedback to show the population that the company is concerned about community issues; and detailing the environmental and social impacts in the company's website. By doing so, the trust of all parties increases, seeing that the company provides clear and accessible information about its activities and social and environmental commitments.

### 5.3 Strategic Partnerships with NGOs and Local Institutions:

The objective is to strengthen ties with non-governmental organizations (NGOs) and local institutions to contribute to the implementation of sustainable projects and mitigate negative impacts. This involves forming partnerships with environmental and social NGOs, preferably those in the Northeast region, and helping to develop initiatives that contribute to environmental preservation. Promoting conversations and public consultations with stakeholders to address issues collaboratively can also be effective. By doing so, local knowledge and NGO expertise can be leveraged to implement sustainable and effective practices, strengthening the company's legitimacy.

These strategies aim not only to address critical challenges but also to reinforce Enel Green Power's commitment to sustainability and the well-being of the communities where the company operates.

## 6. Final considerations

In conclusion, this case study explored the non-market strategies adopted by Enel Green Power to address the socio-environmental challenges associated with the expansion of the wind energy sector in the Northeast of Brazil. The analysis revealed that, despite the economic and environmental benefits brought by renewable energy projects, the company faces significant pressures from various stakeholders and non-market institutions. Initially, the importance of community engagement and environmental education strategies was discussed, highlighting the need to build trust and awareness within local communities. Initiatives such as educational programs and volunteer work proved effective in improving acceptance of Enel Green Power's projects and reducing community conflicts.

Additionally, the strategy of transparency and corporate social responsibility was emphasized as essential for strengthening the company's reputation and gaining stakeholder trust. Publishing sustainability reports and establishing transparent communication channels are crucial steps to demonstrate Enel Green Power's commitment to responsible environmental and social practices.

Moreover, the strategy of strategic partnerships with NGOs and local institutions was presented as an effective way to mitigate negative impacts and promote sustainable development. These partnerships not only leverage local knowledge and NGO expertise to implement sustainable practices but also strengthen the company's legitimacy in the eyes of local communities. Together, these non-market strategies help Enel Green Power address current challenges while positioning the company for sustainable and socially responsible operations in the Northeastern wind market. Enel Green Power navigates Brazil's regulatory and political complexities to expand its operations. Interaction with the government, compliance with strict environmental standards, and investment in social responsibility are essential components for the success of its projects and for the sustainable growth of wind energy in the region. The success of these strategies depends not only on effective implementation but also on the company's ongoing commitment to transparency, community engagement, and sustainable innovation.

These institutional influences, coupled with non-market strategies, create a conducive environment for the development of new clean energy initiatives, strengthening Enel Green Power's position as a leader in the sector and promoting economic, social, and environmental benefits for the Brazilian Northeast.

Therefore, it is recommended that Enel Green Power continue to enhance its non-market practices, adapting to regulatory changes and stakeholder expectations to sustain its growth and positive impact in the Northeast of Brazil. This conclusion summarizes the main findings and recommendations of the study, providing a comprehensive view of Enel Green Power's non-market strategies in the Northeast region of Brazil. Finally, it is noted that, despite growth and profitability in various regions, the company faces financial challenges in the Northeast. Costs associated with the installation and operation of wind farms, along with potential project delays due to bureaucratic and regulatory issues, can impact financial results. Enel Green Power's non-market strategies involve managing relationships with local governments and communities, as well as engaging in social and environmental responsibility actions, which are essential for mitigating risks and ensuring social acceptance of its projects.

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# Facile electro-co-polymerization of polyaniline-poly(3,4-ethylenedioxythiophene) on flexible carbon fiber electrodes for supercapacitor applications

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## Abstract

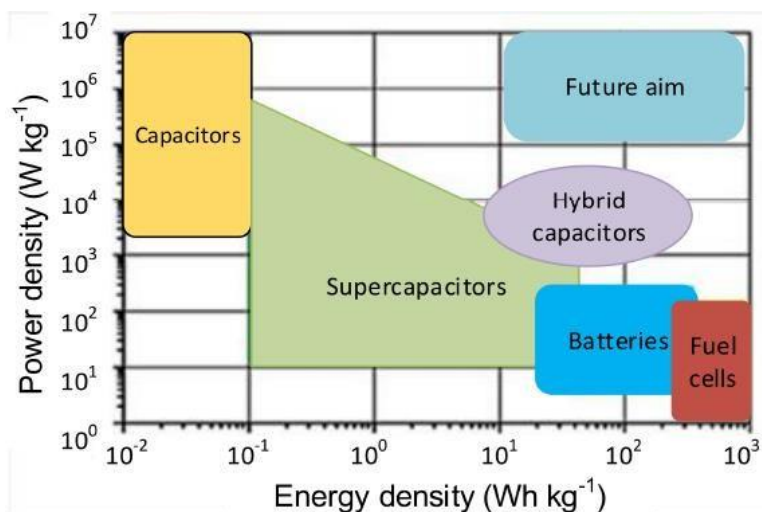
Carbon fiber-based supercapacitors are promising technologies for energy storage in flexible structures and renewable energy sources because they have higher power density, long service life, high flexibility, mechanical strength and fast response, compared to traditional energy storage. In this study, carbon fiber electrodes were coated with Polyaniline (PANI) and Poly(3,4-ethylenedioxythiophene) (PEDOT) films, in different concentrations, through a simple electrodeposition technique by cyclic voltammetry. The electrodes were electrochemically characterized by Galvanostatic Charge- Discharge (GCD) techniques at different current densities and Cyclic Voltammetry with different scanning rates. The electrodes produced exhibited a maximum capacitance per unit area equal to 500 F.cm<sup>-2</sup> with a current density of 2 A cm<sup>-2</sup>. The GCD curves showed good symmetry and relatively low internal loss. This work offers a simple, cost-effective and easily reproducibility method for the manufacture of flexible carbon fiber electrodes coated with PANI-PEDOT films with the possibility of applications in wearable technologies and portable structures.

Keywords: Carbon fiber. PANI. PEDOT. electrochemical storage. supercapacitors

## 1 Introduction

Severe global climate change and successive technological advances have made clean energy sources a global concern. However, the intermittent nature of renewable energy sources has made it essential to develop devices with high storage capacities supercapacitors (SCs), which have developed considerably in recent decades, have emerged with the potential to meet these needs, offering high energy and power densities, as well as a long lifespan that can exceed 100,000 charge and discharge (Pinho, 2018, Olabi et al., 2021, Ai et al., 2022, Sayed et al., 2023).

Batteries and capacitors are both energy storage devices with distinct characteristics that cater to specific needs. Batteries are preferred for applications requiring high energy density and continuous supply, although their energy delivery rate is limited. They are ideal for long-term storage situations but lack the ability to deliver energy quickly. In contrast, capacitors are optimized for applications that require rapid and intense energy discharge. While they have a lower energy density compared to batteries, they can deliver energy at high power, making them suitable for different contexts. However, both batteries and capacitors have significant limitations in scenarios that demand both high energy density and high power simultaneously. This gap has driven research and development into new storage technologies, such as supercapacitors, also known as ultracapacitors. Supercapacitors are energy storage devices that have higher power and energy densities than conventional batteries and capacitors as shown in Fig. 1 (Kim et al., 2015, Najib and Erdem, 2019).



**Figure 1** – Comparison of the energy and power density of energy storage systems (Şahin et al., 2022).

These characteristics have attracted attention to research with supercapacitors that have revealed promising advances, such as using supercapacitors. multi- functional materials in the coating of porous electrodes, offering greater surface area and better conductivity, guaranteeing these devices' electrochemical energy conversion capacity associated with electrolytic storage mechanisms (Najib & Erdem, 2019, Yaseen et al., 2021, Li et al., 2023, Samyn et al., 2023).

Electrodes are fundamental parts of supercapacitors, being essential for charge retention and where electrochemical reactions occur when coated with active materials. Thus, it is desirable that the materials that make up the electrodes have specific characteristics, such as those presented by carbon fibers, which have a high surface area, it is highly flexible and light, in addition to having low electrical resistivity, energy storage capacity, low cost, making them promising for applications in supercapacitors, wearable technologies and nano-technologies. (Choi et al., 2010, Medeiros et al., 2012,).

The use of functional active materials, such as hexacyanoferrates, conductive polymers and organic dyes, in the coating of the electrodes, provides them with electrochemical characteristics for storing electrical charges. Among the conductive polymers, polyaniline (PANI) stands out as a material widely used in the coating of electrodes applied to supercapacitors (Park & Seo, 2012, Samyn et al., 2023). Derived from aniline, it has characteristics such as: easy preparation, electrochemical stability, good electrical conductivity, redox reversibility and relatively low cost. Poly(3,4- ethylenedioxythiophene) (PEDOT) is a conductive polymer that is easy to be processed into thin films or 3D structures and produced from the monomer 3,4-ethylenedioxythiophene (EDOT) by chemical oxidation or electrochemical polymerization.

Herein, carbon fiber electrodes were coated with PANI-PEDOT films through electro copolymerization technique. The electropolymerization process was carried out using cyclic voltammetry (CV) in H<sub>2</sub>SO<sub>4</sub> electrolyte. The electrochemical properties of the electrodes were analyzed by CV with different scan rates and different current densities of GCD. (Medeiros et al., 2012, Park & Seo, 2012). The high specific capacitance of 459 F.cm<sup>-2</sup> at 1 A.cm<sup>-2</sup> was obtained in PANI-PEDOT3 electrode, and the electrode was compared with PANI-PEDOT1, PANI-PEDOT2, PANI and PEDOT electrode, respectively.

## 2 Experimental Procedures

Figure 2 shows the flexible carbon fiber used as the base electrode. The electrode has dimensions 1 cm x 3 cm, good mechanical strength, high flexibility and good electric conductivity.



**Figure 2** – Flexible carbon fiber electrode.

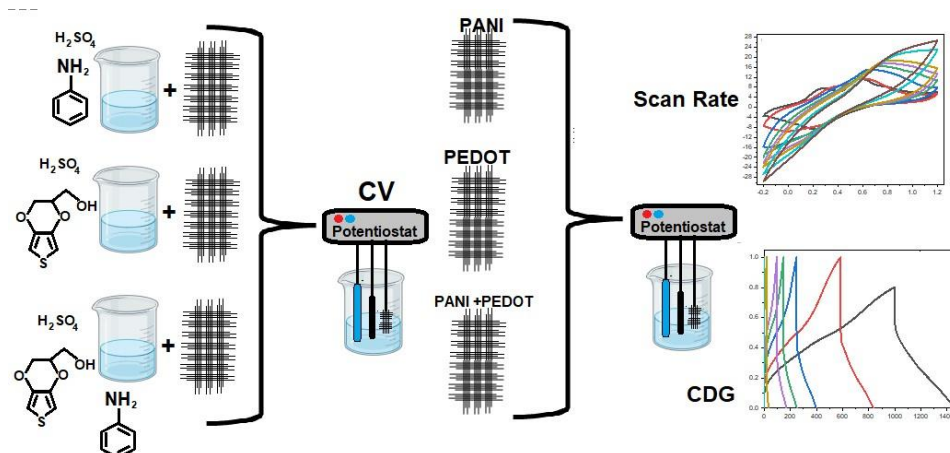
In the electrodeposition of PANI-PEDOT films, the carbon fibers were immersed in solutions containing 0.23 mL aniline monomer with different concentrations (0.01, 0.02, and 0.03 M) of 3,4-ethylenedioxythiophene monomer in 1 M sulfuric acid. This solution was placed in an electrochemical cell connected to an IVIUM COMPACTSTAT® potentiostat using a three-electrode topology. The use of sulfuric acid as an electrolyte in carbon fiber supercapacitors is justified by its high ionic conductivity and ability to enhance specific capacitance through the interaction of H<sup>+</sup> ions with the porous structure of carbon fiber, forming an efficient double layer. Moreover, H<sub>2</sub>SO<sub>4</sub> exhibits remarkable chemical stability over a wide temperature range, ensuring that the electrolyte does not easily degrade over time, maintaining the efficiency and lifespan of the supercapacitor (Pathak et al., 2024).

Aniline, through its derivative polymer, polyaniline (PANI), is extensively studied for its conductive properties. PANI is notable for its high electrical conductivity, attributed to its high level of doping, and its stability. This polymer is particularly efficient in electrostatic processes, making it ideal for applications requiring high power and rapid charge-discharge cycles. The morphology of PANI's nanostructures, such as nanofiber formation, increases the material's surface area, enhancing electron transfer and energy storage capacity. Various polymerization methods can be used to obtain PANI nanostructures, with interfacial polymerization being highlighted for its simplicity and cost-effectiveness. (Liu et al., 2020; Zarshad et al., 2021).

EDOT, on the other hand, is a monomer that results in the polymer poly(3,4-ethylenedioxythiophene) (PEDOT), known for its high electrical conductivity and transparency. PEDOT achieves exceptional electrical conductivity (4500 S/cm) when deposited from the vapor phase. This material is widely used as an electrode in electronic devices, such as solar cells, touch screens, and liquid crystal displays (LCDs). Moreover, PEDOT-based materials are promising for flexible solid-state supercapacitors due to their combination of high conductivity and mechanical flexibility. Most advanced supercapacitors use electrochemical deposition of PEDOT, providing intimate electrical contact and reducing contact resistance between the polymer and the current collector (Kayser and Lipomi, 2019; Wang et al., 2021; Teng et al., 2022; Akbar et al., 2023).

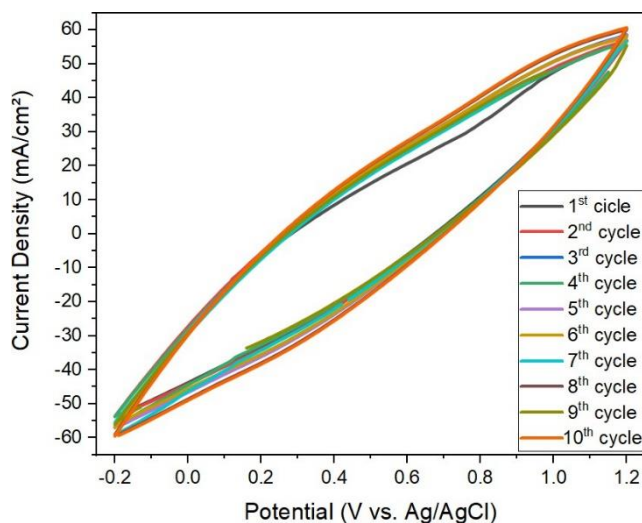
The combination of aniline and EDOT results in a significant advantage due to the complementary properties of their derived polymers, polyaniline (PANI) and poly(3,4-ethylenedioxythiophene) (PEDOT). PANI provides high electrical conductivity and stability, making it ideal for applications requiring rapid charge-discharge cycles, while PEDOT contributes exceptional conductivity and flexibility. Together, these characteristics enhance the efficiency and performance of electronic devices and supercapacitors, offering a combination of high conductivity, stability, and mechanical flexibility.

Figure 3 shows the three-electrode system with the carbon fiber as the working electrode (WE), a silver/silver chloride reference electrode (RE), and a platinum counter electrode (CE). The operation of this instrument is based on applying a potential between the WE and the RE, accompanied by a current flow between the WE and CE electrodes, promoting the deposition of the material on the electrode surface. The coated area of PANI-PEDOT carbon fiber was about 1 cm<sup>2</sup> measured in vernier caliper.



**Figure 3** – Three-electrode topology for carbon fiber copolymerization.

Figure 4 shows the carbon fiber was electrochemically copolymerized with a constant sweep rate of 100 mV/s in a potential window of -0.2 to 1.2 V for 10 continuous cycles in 1 M H<sub>2</sub>SO<sub>4</sub>. At this potential, the PANI-PEDOT film was electroplated on the surface of the carbon fiber, as shown in Figure 3, where one can identify the formation of the film through the linear growth of the current peak due to the growth of the copolymer film. The fabricated electrodes were named as PANI- PEDOT1, PANI-PEDOT2 and PANI-PEDOT3.



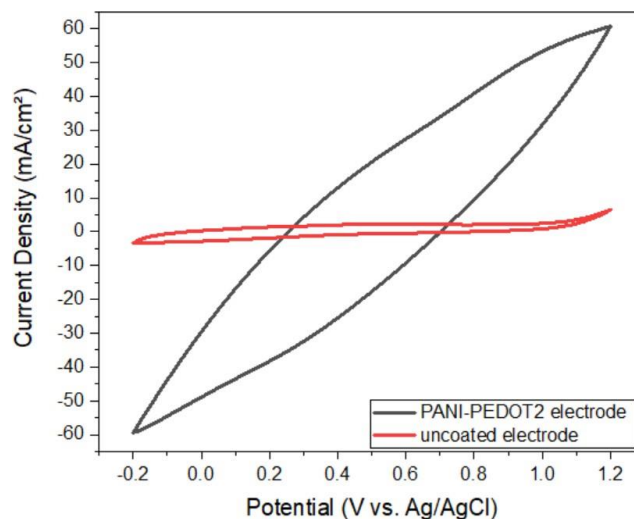
**Figure 4** – Electropolymerization of PANI-PEDOT film on carbon fiber using cyclic voltammetry.

After the electrodeposition process, the electrode was washed with double distilled water to remove undeposited materials from the electrode surface and subjected to air drying. The mass of the electrode before and after the process was measured using a Marte BL320H electronic balance. The area of active material electrodeposited on the electrode surface is approximately 1 cm<sup>2</sup>.

### 3 Results and Discussion

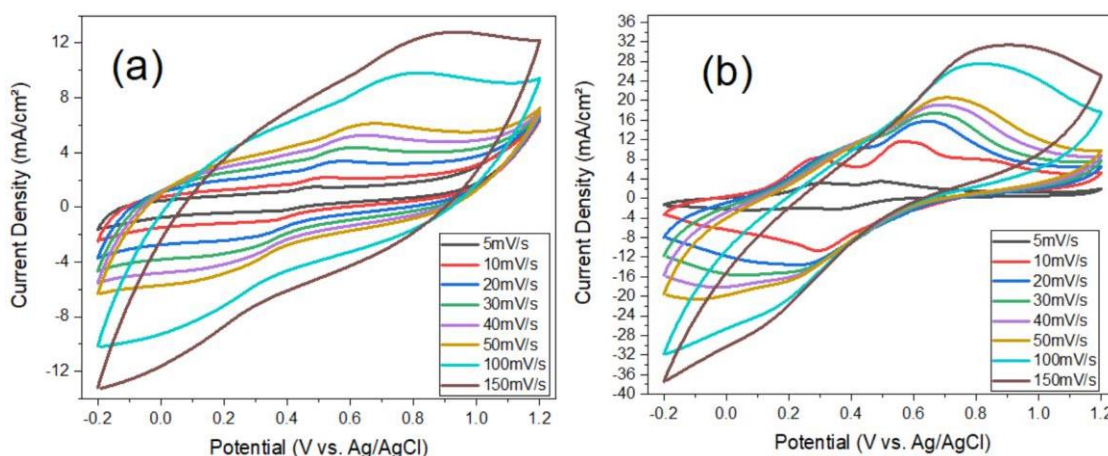
Figure 5 shows the Cyclic Voltammetry curves of the bare carbon fiber electrode, and the electrode coated with the PANI-PEDOT film. The curves reveal the electrostatic and electrochemical currents generated by charges dispersed in the electrolyte and redox reactions on the electrode surface, when a potential of 100 mV/s is applied in a potential window of -0.2 to 1.2 V. The characterization was performed

with the electrode immersed in a 1.0 M 1 M H<sub>2</sub>SO<sub>4</sub> solution.



**Figure 5** – Comparison of CV curves of uncoated carbon fiber and PANI-PEDOT2 coated with carbon fiber at the scan rate of 100 mV/s.

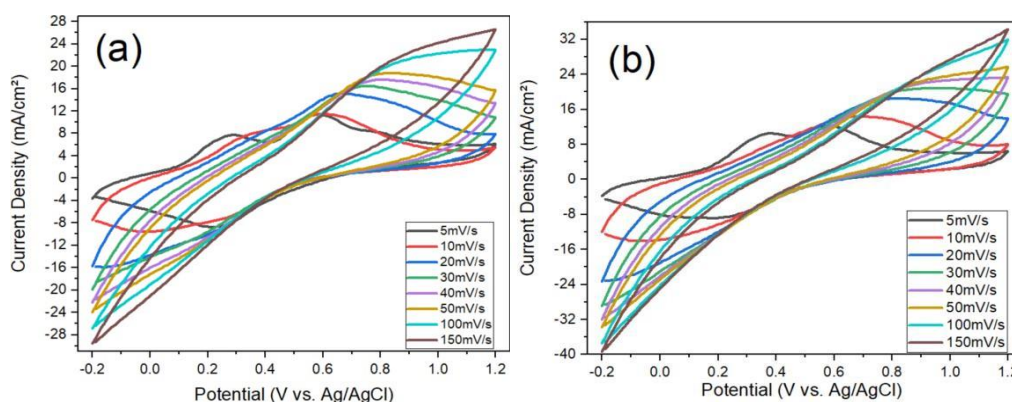
Figure 6 shows the Cyclic Voltammetry curves with different scan rates, ranging from 5 to 150 mV/s for carbon fiber electrodes polymerized with PANI and PEDOT separately. In Figure 5(a), the electrode polymerized with 0.01 M PEDOT shows, at lower scan rates, small amplitude oxidation and reduction peaks accompanied by an increase in electrostatic current that grows in intensity with increasing scan rate, a behavior characteristic of Electrical Double Layer Capacitor (EDLC). In Figure 5(b), the Cyclic Voltammetry of the electrode polymerized with 0.05 M PANI displays, at lower scan rates, the characteristic oxidation and reduction peaks of aniline oxidation stages. Increasing the scan rate prioritizes the rapid reactions occurring on the electrode surface, such as ion adsorption, enhancing the double layer effect.



**Figure 6** – Cyclic voltammetry curves of carbon fiber electrodes polymerized with: a) PEDOT 0.01 M and b) PANI 0.05 M with various scan rates from 5 to 150 mV/s

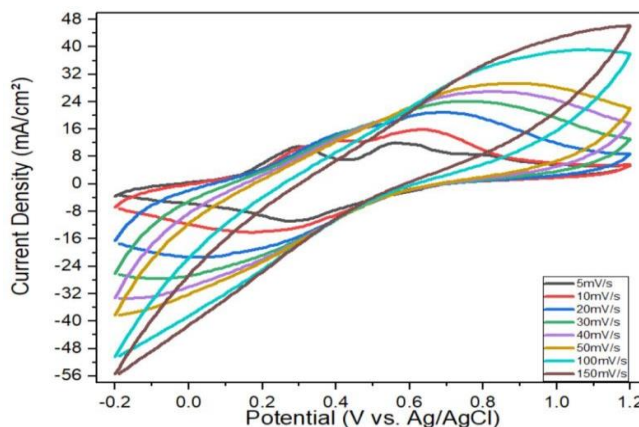
Figure 7 shows the Scan Rate curves of two carbon fiber electrodes copolymerized with PANI- PEDOT. The curve in Figure 6(a) shows the electrode coated with a film of the lowest PEDOT concentration (0.05 M PANI + 0.01 M PEDOT). The oxidation and reduction peaks of aniline can be observed at lower scan rates. As the scan rates increase, the slower electrochemical reactions are replaced by faster ones, leading to a reduction in the peaks and a prioritization of the EDLC behavior. A similar behavior can be observed in Figure 6(b) (0.05 M PANI + 0.02 M PEDOT), with a more significant contribution from the electrostatic current provided by the increased

PEDOT concentration.



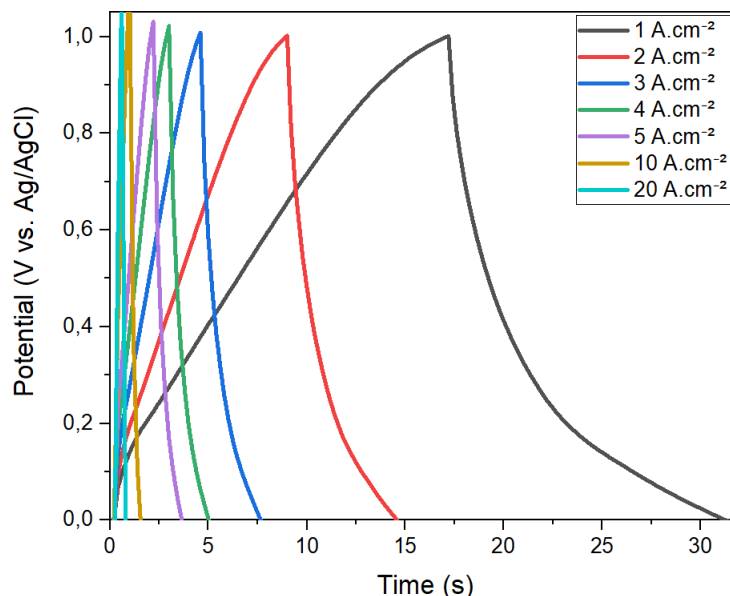
**Figure 7** – Cyclic voltammetry curves of carbon fiber electrodes coated with: a) PANI-PEDOT1 b) PANI-PEDOT2.

Figure 8 presents the cyclic voltammetry curves of the electrode with 0.05 M PANI + 0.03 M PEDOT at different scan rates, ranging from 5 to 150 mV/s. At the lower scan rates, the oxidation and reduction peaks characteristic of aniline oxidation are clearly visible. However, as the scan rate increases, it becomes faster than the rate of the electrochemical reactions, which is observed by the absence of oxidation and reduction peaks in the CV curve, accompanied by an increase in the electrostatic current.



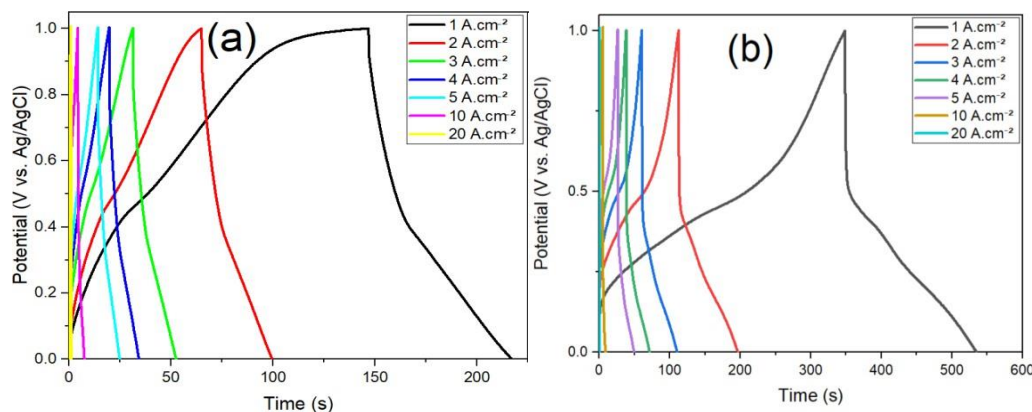
**Figure 8** – Cyclic voltammetry curves of carbon fiber electrode coated PANI-PEDOT3 with various scan rates between 5 and 150 mV s<sup>-1</sup>.

Electrochemical characterization by Galvanostatic Charge and Discharge (GCD) is essential for evaluating the performance of electrodes under charging and discharging conditions with different current densities, ranging from 5 to 20 A.cm<sup>-2</sup>. Figure 9 shows the GCD curves for the bare carbon fiber electrode. The symmetry in the charge and discharge segments of the curve is characteristic of typically EDLC electrodes. This is primarily due to the porous nature of the electrode and the accumulation of charges on the carbon fiber surface, without the occurrence of electrochemical reactions. The rapid drop in potential at the beginning of the discharge is attributed to internal losses that lead to a quicker dissipation of current.



**Figure 9** – Charge and discharge curve of the uncoated carbon fiber electrode at various current densities.

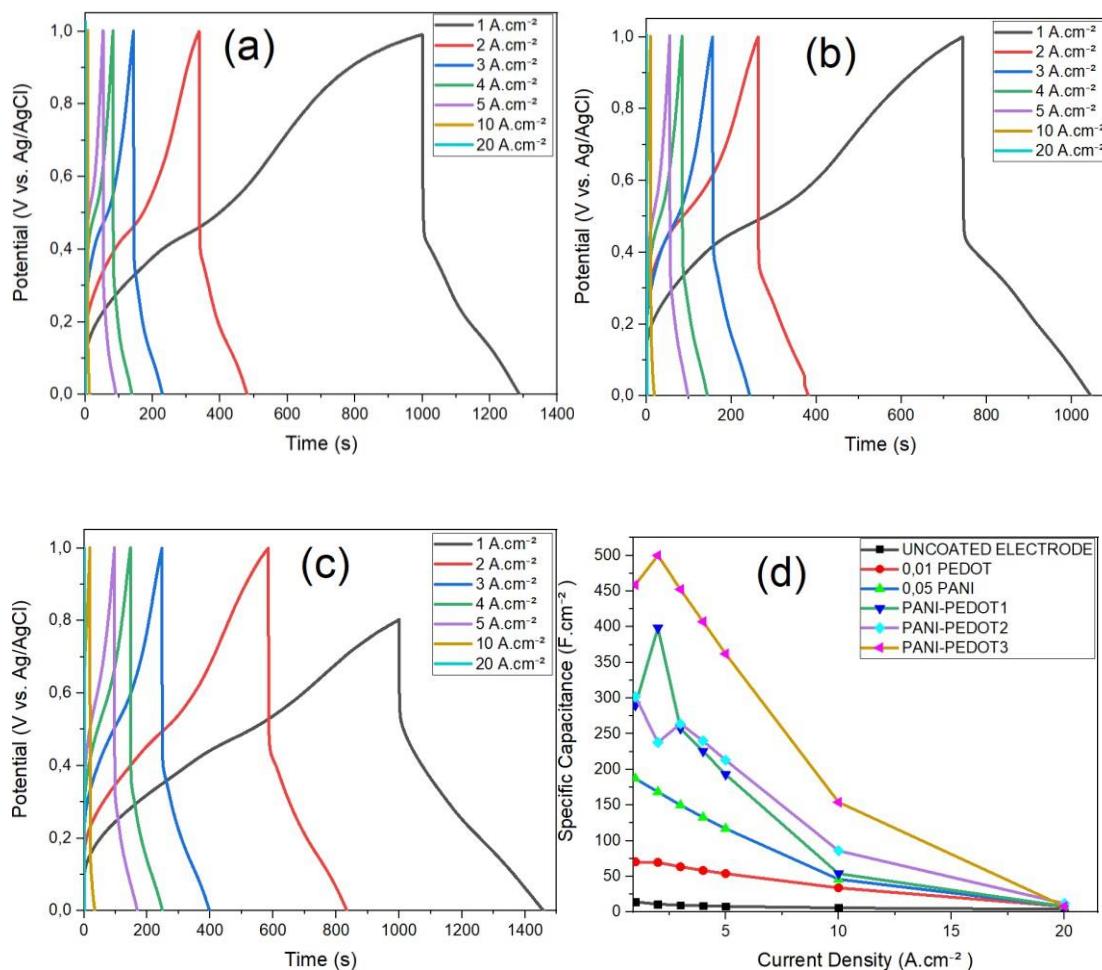
Figure 10 shows the Charge and Discharge curves for the carbon fiber electrodes coated with PEDOT and PANI, respectively. In Figure 9(a), the carbon fiber electrode coated with 0.01 M PEDOT shows a charge accumulation behavior with a degree of symmetry consistent with the characteristics of the conductive polymer. In Figure 9(b), the curve for the carbon fiber electrode coated with 0.05 M PANI displays a charging and discharging behavior occurring at the redox potentials (below +0.60V) of the polyaniline coating, characteristic of active materials and pseudocapacitive electrodes.



**Figure 10** – Charge and discharge curves for the carbon fiber electrodes coated with PEDOT and PANI at various current densities.

Figure 11 (a)-(c) presents the Galvanostatic Charge and Discharge curves for carbon fiber electrodes coated with PANI-PEDOT. All electrodes exhibit symmetric triangular shapes, typical of predominantly EDLC capacitors. However, it is interesting to observe the changes in the discharge curve slopes, influenced by the redox potential's characteristic of PANI, suggesting a pseudocapacitive contribution to the charge storage process of the electrodes. The area capacitance reached its highest value of 500 F.cm<sup>-2</sup> for the 0.05 M PANI + 0.03 M PEDOT electrode at a low current density of 2 A.cm<sup>-2</sup>, compared to 11.2 F.cm<sup>-2</sup> for the bare carbon fiber, 69.6 F.cm<sup>-2</sup> for the electrode coated with 0.01 M PEDOT, and 168.4 F.cm<sup>-2</sup> for the

electrode coated with 0.05 M PANI at the same current density. Figure 11(d) The graph shows that the uncoated electrode has the lowest specific capacitance at all current densities. The electrode with 0.01 PEDOT initially improves, but its efficiency quickly declines as the current density increases. In contrast, the electrode with 0.05 PANI exhibits the highest capacitance, although it also experiences a reduction at high currents. Electrode combinations with PANI and PEDOT, especially the PANI-PEDOT3, stand out for their excellent performance, maintaining high capacitance even at elevated currents. The combination of PEDOT and PANI results in superior electrochemical performance, providing better charge storage and greater stability under various current conditions, demonstrating the effectiveness of the interaction between the two problems in enhancing both conductivity and electrode efficiency.



**Figure 11** - Charge and discharge curves of carbon fiber electrodes coated with: (a) PANI- PEDOT1, (b) PANI-PEDOT2, and (c) PANI-PEDOT3, (d) specific capacitances at different current densities.

From the data obtained from the Galvanostatic Charge and Discharge curves, the specific capacitances  $C$  were calculated using the equation shown in Eq. (1), where  $I$  is the current density,  $t$  is the discharge time,  $V$  is the potential window during discharge, and  $A$  is the area coated with active material.

$$C = \frac{I \times t}{V \times A} \quad (1)$$

The relationship between the area capacitance and the current density is illustrated in Table 1.

**Table 1** – Specific Capacitance at Different Current Densities.

Current Density (A.cm <sup>-2</sup> )	Specific Capacitance (F/cm <sup>2</sup> )					
	Uncoated electrode	0.01 PEDOT electrode	0.05 PANI electrode	PANI-PEDOT1 electrode	PANI-PEDOT2 electrode	PANI-PEDOT3 electrode
<b>1</b>	14.2	70.4	187.2	290.0	302.0	459.0
<b>2</b>	11.2	69.6	168.4	398.4	238.0	500.0
<b>3</b>	9.6	63.6	150.0	257.4	264.0	452.4
<b>4</b>	8.8	58.4	132.8	225.6	240.0	407.2
<b>5</b>	8.0	54.0	117.0	193.0	213.0	362.0
<b>10</b>	6.0	34.0	46.0	54.0	86.0	154.0
<b>20</b>	4.0	8.0	8.0	8.0	12.0	8.0

Table 1 illustrates the correlation between current density and specific capacitance for different electrodes, highlighting substantial variations between uncoated electrodes and those coated with conducting polymers such as PEDOT, PANI, and their combinations. The uncoated electrode exhibited the lowest capacitance values, starting at 14.2 F.cm<sup>-2</sup> at 1 A.cm<sup>-2</sup> and gradually decreasing to 4.0 F.cm<sup>-2</sup> at 20 A.cm<sup>-2</sup>. This behavior reflects its low efficiency in storing electrical charge, limiting its application in high-energy-demand devices. Electrodes coated with PEDOT showed superior performance, with an initial capacitance of 70.4 F.cm<sup>-2</sup> at 1 A.cm<sup>-2</sup>. However, this advantage quickly diminished as the current density increased, resulting in only 8.0 F.cm<sup>-2</sup> at 20 A.cm<sup>-2</sup>. This suggests that while PEDOT provides a significant initial improvement, it cannot sustain its performance under higher demand conditions. The coating with PANI, in turn, revealed a distinct behavior, with a considerably higher initial capacitance, reaching 187.2 F.cm<sup>-2</sup> at 1 A.cm<sup>-2</sup>, but also showing a steep decline at higher current densities, dropping to 8.0 F.cm<sup>-2</sup> at 20 A.cm<sup>-2</sup>. Although PANI outperforms PEDOT in terms of initial storage capacity, it faces similar challenges in maintaining efficiency at high currents.

Electrodes coated with the combination of PEDOT and PANI, specifically the PANI-PEDOT electrodes, demonstrated the excellent supercapacitive performance. PANI-PEDOT1 achieved 290.0 F.cm<sup>-2</sup> at 1 A.cm<sup>-2</sup>, maintaining 54.0 F.cm<sup>-2</sup> at 10 A.cm<sup>-2</sup> and dropping to 8.0 F.cm<sup>-2</sup> at 20 A.cm<sup>-2</sup>, showing greater stability compared to electrodes coated with individual polymers. PANI-PEDOT2 performed slightly better at low current densities, with 302.0 F.cm<sup>-2</sup> at 1 A.cm<sup>-2</sup> and 86.0 F.cm<sup>-2</sup> at 10 A.cm<sup>-2</sup>, but also saw its capacitance reduced to 8.0 F.cm<sup>-2</sup> at 20 A.cm<sup>-2</sup>. The best-performing electrode was PANI-PEDOT3, with an impressive specific capacitance of 459.0 F.cm<sup>-2</sup> at 1 A.cm<sup>-2</sup> and 154.0 F.cm<sup>-2</sup> at 10 A.cm<sup>-2</sup>, demonstrating great stability and efficiency at intermediate current densities. The data analysis reveals that the combination of PEDOT and PANI is particularly effective, as it provides a synergy that maximizes charge storage capacity and optimizes the distribution of electrons and ions at the electrode/electrolyte interface. This hybrid approach has proven superior to solutions based on individual polymers, offering a robust strategy to improve the electrochemical performance of carbon fiber electrodes. The high performance of the PANI-PEDOT3 electrode highlights the potential of this combination to drive advancements in supercapacitor technology, paving the way for the development of materials with greater energy storage capacity and efficiency in high-demand applications.

## 4 Final Considerations

In summary, a uniform PANI-PEDOT film was coated onto a carbon fiber electrode through a simple electrodeposition process. The presence of an electrochemical charge storage mechanism, facilitated by the PANI-PEDOT combination on the carbon fiber surface, was observed in the peaks present in the Cyclic

Voltammetry curves and Galvanostatic Charge and Discharge graphs. Considerable electrostatic storage was also observed, primarily driven by the porosity of the carbon fiber, combined with the characteristics of the copolymeric film. A good area capacitance was achieved with the carbon fiber electrode coated with a 0.05 PANI + 0.03 PEDOT film, reaching 500 F.cm<sup>-2</sup> at a current density of 2 A.cm<sup>-2</sup>, which is higher compared to the electrodes coated with PANI-PEDOT films with lower PEDOT concentrations: 398.4 F.cm<sup>-2</sup> (0.05 PANI + 0.01 PEDOT) and 238 F.cm<sup>-2</sup> (0.05 PANI + 0.02 PEDOT) at the same current density.

This study presents a straightforward and economical approach to produce flexible carbon fiber electrodes that are coated with PANI/PEDOT films. These electrodes have the potential to be used in wearable technology and portable constructions.

## Acknowledgments

A.L.F.B. acknowledge the Brazilian organizations CAPES, CNPq (Bolsa de Produtividade 30.7418/2021-9 and 30.4511/2022-6) and FAPERJ (E-26-210.965/2021, E-26-210.801/2021, E-26-245.307/2019, E-26-202.549/2019, E-26/201.934/2019, E-26-00.320/2023, and E-26/201.622/2023), FINEP (Convênio nº 04.19.0040). A.M.S.R., M.P.A. and V.S.L. acknowledge CAPES FUC-01, R.S.B. FAPERJ (E-26/202.465/2023) and CAPES (88887.798322 / 2022-00).

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# Biogas Purification from Landfill Gas by Adsorption

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## Abstract

The study conducted at the Polytechnic Institute of Bragança (IPB) investigated techniques for harnessing and treating gases released from anaerobic digestion. Initially, a systematic literature review was conducted on the upgrading process, i.e., the transformation of biogas into biomethane, using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method associated with bibliometric analysis. Subsequently, an experimental analysis was developed applying the Pressure Swing Adsorption (PSA) method, a purification method still not widely popular commercially, mainly used in the removal of CO<sub>2</sub> and other gas components from biogas. Thus, the study evaluated CO<sub>2</sub> removal in PSA using a specific type of activated carbon known as Carbon Molecular Sieve (CMS). This analysis allowed understanding the CO<sub>2</sub> adsorption capacity and the affinity of CMS-3K with methane. Furthermore, a detailed analysis was conducted using a specific bibliographic data processing method, allowing a comprehensive understanding of the scenario. Academic collaborations among key countries were identified, promoting knowledge and technology exchange, suggesting that relationships between countries, influenced by historical, economic, and cultural factors, play an important role in scientific collaboration. The research highlights that the PSA technique using carbon molecular sieves is a promising alternative for biogas purification into biomethane, although still not widely disseminated. The development and application of this technology can improve urban solid waste management, generate versatile renewable fuel, and reduce greenhouse gas emissions, thus promoting sustainable development and contributing to global energy transition.

## 1 Introduction

The use of new technologies to prevent, mitigate and remedy the adverse effects of GHGs is essential to achieving sustainable development and meeting climate targets. Therefore, the use of biofuels, renewable energies and the implementation of practices based on the circular economy offer significant socio-environmental advantages, ranging from reducing greenhouse gas emissions, replacing fossil fuels, increasing efficiency in energy generation and economic development based on sustainability (Mignogna et al., 2023). This low-carbon gas can be widely used to generate heat for energy, electricity and domestic activities such as cooking and heating. However, to extend its use, it is

necessary to go through the purification process (upgrading) to convert it into biomethane, with a higher degree of purity, after which this gas can be used as fuel (Bakkaloglu & Hawkes, 2024).

In this context, the generation of biogas becomes an attractive socio-environmental and economic path for countries that have landfills, controlled landfills or rubbish dumps. This biological gas arises from the degradation of organic matter by anaerobic microorganisms in a process known as anaerobic digestion. The application of techniques for separating and purifying this gaseous input derived from waste expands the uses of the different gases produced in the degradation of the organic matter present in municipal solid waste (Sales Silva et al., 2022). Different techniques can be used to separate gases, such as adsorption, absorption, fractional distillation, membranes, diffusion and cryogenics. However, adsorption has a wide range of different applications in industry. Adsorption is defined as a mass transfer operation that studies the ability of certain solids to concentrate certain substances on their surface in liquid or gaseous fluids, allowing these components to be separated. In the process of separating gases, activated carbon is sometimes used as the adsorbent, i.e. the solid material on which the adsorbate is adsorbed, which can be defined as the substance that is adsorbed onto the resistant material (Shen et al., 2021).

The Pressure Swing Adsorption (PSA) process with activated carbon represents a cutting-edge methodology for removing polluting gases from industrial gas streams. Activated carbon, with its extraordinary surface area and intrinsic porosity, provides superior adsorption capacity for a wide variety of gaseous pollutants. In the PSA cycle, the pollutant gas is pressurized and directed through a bed of activated carbon, where the unwanted molecules are efficiently captured on the surface of the adsorbent. Subsequently, the reduction in pressure allows the adsorbed pollutants to desorb, facilitating their removal from the system (Li et al., 2023). Among the different types of activated carbon that can be used in the PSA process, the focus of this study was on commercial activated carbon of the Carbon Molecular Sieve (CMS) type. This material has an optimized microporous architecture that offers exceptional selectivity for oxygen and nitrogen. In addition to its efficiency in gas separation, it stands out for its mechanical resilience and rapid regeneration during depressurization cycles. In this way, the operational versatility of this coal allows it to be applied in various industries, such as nitrogen production and biogas purification (Smith et al., 2023).

The growing challenges related to energy and environmental sustainability make the search for renewable energy sources an undeniable global priority. In this context, upgrading biogas into biomethane through adsorption techniques has emerged as an alternative to removing gases such as CO<sub>2</sub>. This study proposes an innovative approach to biogas purification, exploring the use of CMS-3K activated carbon in the pressure variation adsorption (PSA) process for biomethane production. Therefore, this research seeks to contribute to the advancement of biogas purification technology through technologies that are still little explored to solve environmental problems. This work has the objective evaluate the technique for separating gases contained in biogas from organic waste, using the PSA adsorption method containing activated carbon of the CMS-3K type to remove CO<sub>2</sub> from biogas.

## 2 Review

Biogas is a renewable gaseous fuel generated during the anaerobic decomposition of organic matter by microorganisms. This process occurs in a variety of sources, including agricultural waste, industrial effluents, sewage treatment plants, energy crops and landfill sites. In landfill sites, biogas is produced by the decomposition of organic waste deposited alongside other waste, so in the absence of oxygen, microorganisms break down the organic matter releasing CH<sub>4</sub> and CO<sub>2</sub>. This gas can be captured and used as a low-carbon renewable energy source, helping to reduce greenhouse gas emissions and promoting energy sustainability (Khalid et al., 2021). Purification of this low-carbon gas requires an understanding of the percentage composition of biogas from the different generation sources. Table 1

shows the (reference) values for the main constituents of biogas, as well as the reference values for the composition of natural gas, an important indicator of biomethane purity.

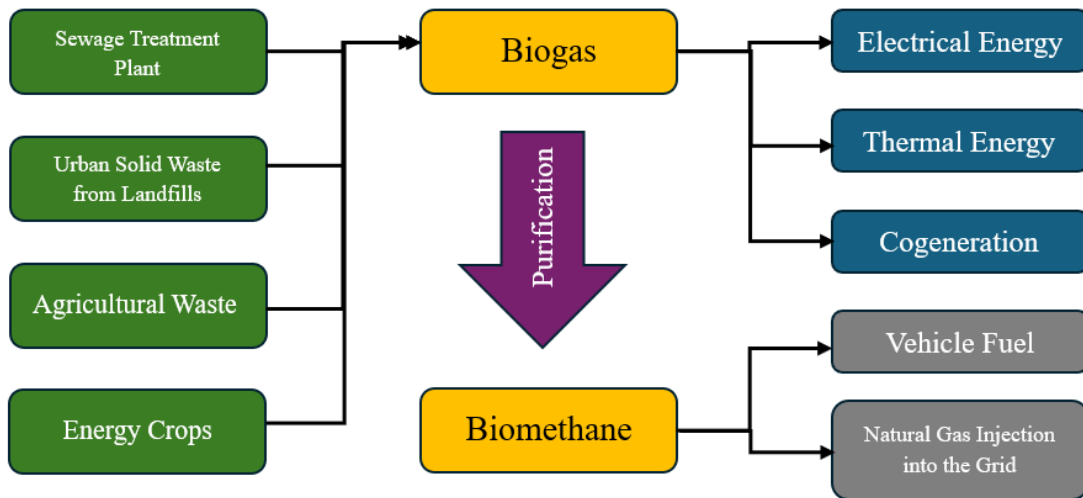
Components	Units	Natural Gas (Portugal)	WWTP/ETE Biogas	Landfill Biogas	Agro-industrial Biogas
Methane (CH <sub>4</sub> )	% vol.	86,5	65-75	45-55	45-75
Carbon Dioxide (CO <sub>2</sub> )	% vol.	≈1	20-35	25-30	25-55
Nitrogen (N <sub>2</sub> )	% vol.	0,3	3,4	10-25	0,01-5,00
Oxygen (O <sub>2</sub> )	% vol.	0,05-2	0,5	1-5	0,01-2,00
Hydrogen Sulfide (H <sub>2</sub> S)	mg/mN <sup>3</sup>	5	<8000	<8000	10-30000
Siloxanes	mg/mN <sup>3</sup>	-	<0,1-5,0	Residual	<0,1-5,0
Lower calorific value (LCV)	MJ/mN <sup>3</sup>	37,9	21,6-27,0	16,2-19,8	18,0-27,0

**Table 2:** Composition of biogas from different sources

**Source:** Adapted from (Monteiro et al., 2011).

The process of transforming biogas into biomethane is called upgrading, the aim of which is to remove impurities using different techniques available on the market. Among the most common technologies is solvent absorption, where CO<sub>2</sub> is removed from biogas by selective absorption in solvents. There is also solid bed adsorption, where CO<sub>2</sub> is adsorbed by solid materials while methane passes through the adsorbent. The use of selective membranes, in which the components of biogas are separated based on the permeability of the gases. In addition, cryogenics is used to cool biogas to very low temperatures, condensing impurities. Chemical desulphurization removes sulphur compounds such as H<sub>2</sub>S. These techniques make it possible to treat biogas and expand its applications as a high-purity renewable fuel (Pavičić et al., 2022).

The conversion of biogas and biomethane presents a great opportunity to add economic value to gaseous effluent and mitigate greenhouse gases that are harmful to people and the environment. According to Sales Silva et al. (2022) there are various applications for biogas, such as the generation of electricity, thermal or mechanical energy, especially in cogeneration systems. In this way, as can be seen in Figure 1, purified biogas (biomethane) can be used as an alternative to natural gas in vehicles or directly inserted into natural gas (NG) distribution networks. These different applications for this renewable fuel demonstrate the important role that biofuels play in the energy transition and how the circular economy can accelerate this process.



**Figure 5:** Production sources and applications for biogas.  
**Source:** Adapted from (Veiga & Mercedes, 2015).

Figure 1 shows that biogas is a versatile renewable gas that can be produced from different sources, such as sewage treatment plants, landfills, agricultural waste and energy crops. Thus, without the purification process (upgrading), biogas is commonly used to produce electricity, heat and cogeneration. However, when this gas goes through the purification process, it ends up expanding the possibilities for its use, such as being used as a fuel and being injected into the natural gas grid associated with it. Therefore, the utilization of biogas is of paramount importance in the fight against climate change, since the production of this input can take place in different scenarios and locations.

Carbon Molecular Sieve (CMS) 3K is a specific type of commercial activated carbon that was adopted in this study to investigate the biogas purification process. This carbon is normally supplied by Osaka Gas Chemicals Co., Japan, and consists of commercial cylindrical pellets with a diameter of 1.8 mm and a length of between 1.18 and 2.8 mm (Zafanelli et al., 2024). However, to ensure that the charcoal works, it needs to go through a pyrolysis and activation process to reach the ideal micropore size for removal (Cavenati et al., 2005). Image 3 below shows the morphology of CMS3K-172, which was assessed by Scanning Electron Microscopy (SEM) in the characterization studies of this element carried out at the Porous Solids Laboratory at the University of Malaga in Spain. Since the molecular-sized pores in CMS provided high kinetic selectivity and adsorption capacity for various gases. Therefore, CMS was chosen in this biogas upgrading study because it allows a higher level of carbon dioxide diffusion in the micropore network than methane molecules ( $\text{CH}_4$ ), which present strong resistance on the surface and inside the micropores of the adsorbent (Kottitum et al., 2020).

In this way, this commercial activated carbon is an option for use in the gas purification process, since its properties can remove the carbon dioxide present in biogas, achieving excellent purity levels. Some research has shown that combining CMS with adsorption technologies, such as pressure swing adsorption (PSA), can achieve excellent purity levels, with up to 97.92% methane in the biogas, demonstrating an opportunity to reduce the commercial costs of the process (Kottitum et al., 2020). In pressure swing adsorption (PSA) processes, the biogas is subjected to compression between 4-10 bar and then fed into a column where it meets an adsorbent material. This adsorbent, such as carbon molecular sieves (CMS), activated carbons, zeolites and other materials such as thitosilicates, can selectively retain the  $\text{CO}_2$  present in the biogas. The purified methane gas ( $\text{CH}_4$ ) is recovered at the top of the column with minimal pressure drop. Thus, over time, the adsorbent becomes saturated with  $\text{CO}_2$ , after which it is necessary to regenerate the column by reducing the pressure (Kohlheb et al., 2021).

Although this process works adequately to remove carbon dioxide, a greenhouse gas, H<sub>2</sub>S is usually irreversible in adsorbents, so a process to remove this gas must be implemented before PSA. Depending on the adsorbent chosen, it is also possible to remove the moisture present in the biogas along with the CO<sub>2</sub> in the same unit. In this method, multi-column matrices are used to simulate a continuous process. However, for smaller-scale applications subject to interruptions, it is possible to use a single column with storage tanks. Thus, one of the main advantages of the PSA process is its adaptability to biogas valorization anywhere in the world, regardless of the availability of hot or cold sources (Shen et al., 2021). The useful life of the carbon molecular sieve is an important factor to consider in gas separation applications. As such, the lifespan of the CMS can vary according to the quality of the material, operating conditions such as gas composition, temperature and pressure, as well as the frequency of regeneration. With proper maintenance and the adoption of correct operating practices, the lifespan of the CMS can be extended, guaranteeing consistent performance over time and potentially exceeding years of operation. However, it is important to regularly monitor the operational performance of this material and replace it when necessary to ensure the efficiency and quality of gas separation processes (Yamtop Chemical Co., 2024).

### 3 Methodology

A systematic literature review was carried out in conjunction with bibliometric analysis. This methodological practice was inspired by the work of SOARES (2023), who advocates the combined use of these two methodologies as a way of comprehensively demonstrating research. The combination of these techniques can demonstrate the evolution of scientific studies over time in a quantitative way using bibliometrics, and qualitatively, through specific studies on themes and content using systematic review (Pizzi et al., 2020).

#### 3.1 Qualitative Analysis Using the PRISM Method

This study used the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta Analyses) protocol to produce the review, allowing for the inclusion of relevant aspects such as literature search, identification of eligible published articles, data extraction and summarization. Priority was given to open access documents from indexed journals around the world. The search strategy was carried out in advanced mode using the following search strings: TS = (PRISMA AND Preferred Reporting Items for Systematic reviews and Meta Analyses), TS = (bibliometrics), TS = (biomethane AND landfill gas), TS = (biogas upgrade), TS = (CMS-3K AND carbon molecular sieve), TS = (PSA AND pressure swing adsorption). All six search strings were combined using the Boolean logical operator OR so as not to obtain duplicate results. In addition, only articles published in English between 01/01/2015 and 01/01/2024 were selected. A total of 29,880 documents were found using the search sequence mentioned above. The data was then exported with full records and references cited and saved in tabular format for later analysis in Microsoft Excel, producing graphs and tables. The research carried out by Boloy et al. (2021) indicates that the Open Refine 3.8 software is recommended due to its compatibility with various data manipulation tasks and its effectiveness in cleaning data, resolving ambiguous information, eliminating redundancies and facilitating data format transformations.

#### 3.2 Quantitative Analysis by Bibliometric

The study of bibliometrics encompasses different quantitative, statistical and mathematical techniques employed to examine and construct indicators relating to patterns and developments in the scientific domain. As a rule, these methods focus on investigating disciplines, areas of study,

organizations or countries. Therefore, the data used for bibliometric analyzes come from important databases of articles dedicated to reputable academic periodicals and magazines (Soares et al., 2023). Data analysis in this study was carried out using the methodology described in Boloy et al. (2021). To facilitate the construction and visualization of bibliometric maps, the researchers used the VOS viewer software. The program offers a comprehensive and easy-to-use approach to building and interpreting bibliometric maps and is free to access. Maps are represented by circles representing individual items, with the size of each circle reflecting the meaning of the respective element, and the connections between items in the network map demonstrating the closeness of their relationships. Furthermore, the position and color of the circles are used to group similar elements (Van Eck & Waltman, 2010). The work considered two bibliometric indicators to carry out this study: co-authorship with countries as a unitary analysis and co-occurrence with author keyword as a unitary analysis.

## 4 Results and Discussion

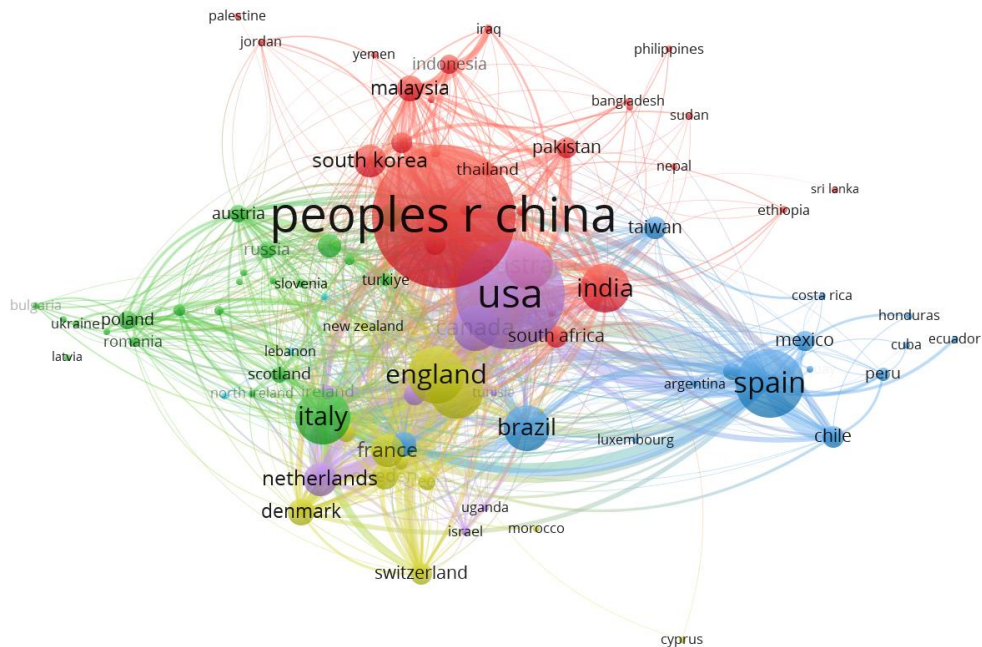
### OVERVIEW OF PUBLICATIONS ON BIOGAS UPDATE USING CMS-3K IN PRESSURE SWING ADSORPTION (PSA)

**CHRONOLOGICAL ANALYSIS OF PUBLICATIONS:** From the search string used in the previously mentioned Web of Science database, 29,880 documents were found that went through a screening process and were refined to 9,374 articles. The average number of publications has increased over the years, and it can be noted that from 2018 onwards the growth rate has increased significantly. The years with the most publications are 2022 and 2024, with 1670 and 1745 articles, respectively.

**GENERAL ANALYSIS OF PUBLICATION KEYWORDS:** Using the VOS viewer software analyzed in Figure 2, 1144 keywords were found in 5 occurrences. After selecting the words that best matched the objective of the work, it was possible to create a visual visualization structure. Furthermore, the most used keyword is "Bibliometrics", with 4053 searches, and the total link strength was 5, followed by "Biogas update", with 435 searches and a total reach strength of 9. Bibliometric analysis "occurred 404 times, with a total link strength of 4. The distance between keywords is proportional to the relationship between them. Therefore, the keyword "Bibliometrics" is very close to "Adsorption", indicating that these concepts possibly originate from each other. The keyword "biogas" is surrounded by the words "CO<sub>2</sub> capture", "activated carbon", "Pressure Swing Adsorption" and "CO<sub>2</sub> utilization". This relationship demonstrates that these terms have a direct relationship, even interdependence, since these terms arise from one another. Furthermore, this connection shows that the work followed a line of reasoning with the potential to develop alternatives for using biogas. On the other hand, the words "biogas update", "biomethane" and "biogas" are still relatively distant, demonstrating the need to promote more research in this field.

**RESEARCH AREAS:** The ten thematic areas of research that presented the most published articles were: Information Science Library Science (1312), Chemical Engineering (884), Energy Fuels (862), Environmental Sciences (769), Interdisciplinary Applications in Computer Science (691), Technology green sustainable scientific (441), Environmental Engineering (416), Surgery (358), General Internal Medicine (326) and Computer Science Information Systems (308).





**Figure 3:** Cooperation between countries.  
**Source:** (Author, 2024).

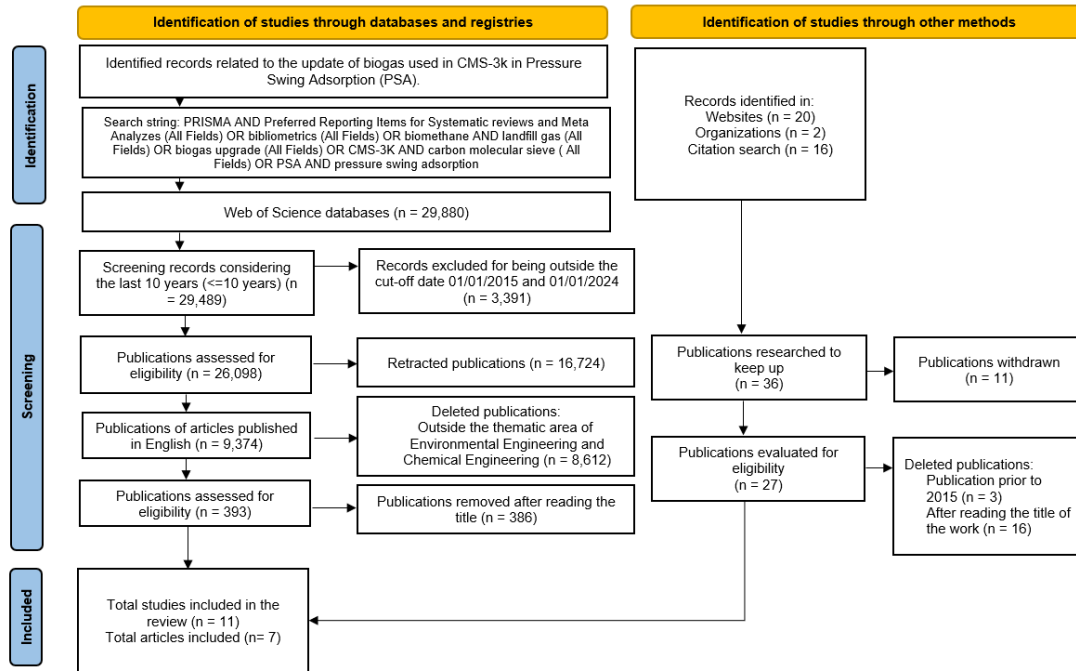
#### SYSTEMATIC LITERATURE REVIEW: PRISMA METHOD

The Figure 4 presents the PRISMA flowchart for the records included in the review based on four stages of the search strategy (identification, screening, eligibility and included). Of the 29,880 documents screened in the Web of Science database, 393 were selected, after discarding the remaining documents due to refinement criteria in the screening stage, such as: considering the year published as 10 years, texts published only in English and thematic area. In relation to the thematic area, 8,612 textual documents that did not belong to the topic in question were discarded. Then, only 7 were selected after reading the title, in which titles without terms such as "carbon molecular sieve", "biomethane", "biogas upgrade", "pressure swing adsorption" and "landfill gas" were discarded. From these documents and after reading the abstract, 7 were included in the meta-analysis. Furthermore, other documents used in the application of the PRISMA method were identified, taken from other sources of information indicated below.

By using organic materials discarded in landfills, biogas not only prevents the production of methane during decomposition, but also reduces dependence on non-renewable fuels, promoting the diversification of the energy matrix. Furthermore, biogas enables more effective management of urban solid waste, reducing the amount of waste sent to landfills and generating additional revenue through the sale of electricity, use as vehicle fuel or injection into the natural gas distribution network (Pérez-Camacho et al., 2019). Despite challenges related to infrastructure and regulation, the potential of biogas as a sustainable fuel is undeniable, requiring appropriate policies and investments for its wide adoption and maximizing its environmental and economic benefits (Cordova et al., 2023).

In view of the above, the upgrading of biogas into biomethane using adsorption processes (PSA) containing carbon molecular sieve (CMS) in the columns is a technique little explored both in the research environment and in industry. Therefore, this work sought to explore this topic due to the importance of the topic considering the technological and scientific advances necessary in the production of high purity biofuels. Given the results obtained, it was possible to see few studies focusing

on the PSA technique using CMS, although there is a strong potential for this combination to remove carbon dioxide present in biogas. In general, this process not only contributes to the mitigation of GHG emissions, by reducing dependence on fossil fuels, but also promotes a more sustainable management of organic waste, aligning with the principles of circular economy and sustainable development.



**Figure 4:** Most relevant research areas.  
**Source:** (Author, 2024).

## 5 Conclusion

Although there are not many published works on the chosen technique, which justifies the need for new studies to further develop this process, both fuels present many socio-environmental and socio-economic advantages. The products generated in the processes can be used in different areas of society, such as heating, electricity generation, cogeneration, injected into the natural gas network and used as vehicle fuel. It concludes that biogas and biomethane are versatile energy transition fuels that can gradually replace the use of fossil fuels in the long term. The PSA adsorption technique with carbon molecular sieve is still little used, considering that the most common are membranes. This technique makes it possible to use methane as fuel, recover carbon dioxide and avoid GHG emissions into the atmosphere. Allowing sustainable development by techniques arising from the circular economy.

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# Evaluation of an ARIMA model for forecasting distributed generation installed power

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## Abstract

Distributed Generation (DG) has a prominent global role when the subject is energy transition since the energy used to generate electricity must be from renewable sources. The development pace of DG in the power grid differs from that of centralized generation, as its diffusion depends on consumer adoption. In contrast, the centralized generation growth rate is mainly regulated by the agency responsible for power sector planning. These growth characteristics of DG have made planning for the power sector particularly challenging, as estimating its growth is inherently complex. This paper aims to evaluate the performance of an ARIMA model to make long-term predictions of DG-installed power. An ARIMA model was developed to estimate the DG installed power in the Brazilian scenario over ten years. This model is compared with the Bass model used by the Brazilian Energy Research Company (EPE - Empresa de Pesquisa Energética) in the PDE34 report. The ARIMA model analyzed demonstrated potential for use in the study scenario, presenting results similar to those of the compared case.

## 1 Introduction

Distributed generation (DG) has been growing in several places worldwide, and the global installed capacity of this generation type totalled 167 GW from 2019 to 2022 (Machado, 2024). DG reached 25 GW of power in Brazil at the end of 2023. DG has a prominent role in the energy transition since the sources used in this generation modality are sustainable. According to Law 14,300, it is only allowed to use solar, wind, biomass, or hydraulic sources in the DG system (of the Republic, 2022). In practice, the photovoltaic solar source is the one that has the most significant prominence among the sources allowed in Brazil; its share is 99.8% in installed capacity (ANEEL, 2024).

This growth resulted in new legislation, as the rules previous to the new Law were prejudicing the Brazilian electricity sector (Silva and Guerrieri, 2020). With the establishment of the new Law, some rules changed; however, the main characteristics remained the same. The main change was in the compensation system, where the amount of energy compensated by prosumers was reduced (ANEEL, 2012; of the Republic, 2022).

These changes reduced DG's growth. The number of monthly DG installations in the country fell sharply; for instance, the monthly average of the installation number in 2022 was reduced from 72,000 to 49,000. The installed power also dropped from 8.31 GW (before the new Law) to 6.71 GW (after the new Law). Reducing the growth of DG installations affects the adoption of clean energy sources, which is detrimental to the current energy transition (ANEEL, 2024).

These changes were implemented to prevent the worsening of the impacts caused by DG. DG-installed power forecasts helped in decision-making, as they showed accelerated growth, which would aggravate the problem. The Brazilian Energy Research Company (EPE - Empresa de Pesquisa Energética) is one of the institutions that forecast the electricity sector in Brazil. A report of possible

scenarios is released annually over a 10-year horizon of the energy sector, and DG is included in this report (EPE, 2024). EPE pointed out that making forecasts for DG is complex because, unlike what happens with centralized generation systems, the growth of DG-installed power is like the diffusion of a product in the market, which has the final consumer's decision as a variable (EPE, 2022).

The uncertainty degree of the DG market growth is great, causing a problem for national energy planning because predicting a high DG insertion can incorrectly anticipate wrong decision-making or even oversize investments in infrastructure (EPE, 2022). In this context, it is necessary to be as assertive as possible in forecasting, and the choice of methodology is a key point.

In the literature, several articles are found that make forecasts of the electricity sector, and a few different methodologies are used, as shown in the review article (vom Scheidt et al., 2020). In (Radomes Jr and Arango, 2015), the authors build a Bass diffusion model incorporating subsidy and feed-in-tariff policies to predict the DG diffusion in Medellín, Colombia. The article (Da Silva, Uturbey, and Lopes, 2020) also projected DG diffusion in Brazil, using the Bass diffusion model but incorporating the adoption of solar water heaters as a parameter. The article (Islam, 2014) uses forecasting with the Bass diffusion model to suggest strategies to spread DG in Canada.

Other articles have combined methodologies for the forecasts. For instance, (V. Costa et al., 2022) combines the Bass diffusion model with the optimized tariff model (socioeconomic regulated electricity market model). (V. B. Costa et al., 2022) performs a similar work but uses two methods beyond the Bass diffusion model, the optimized tariff model and the life cycle assessment (an environmental impact analysis technique) to make the predictions. The authors aim to forecast with a holistic assessment, including the Bass diffusion model's environmental impacts and financial indicators.

The article (V. B. Costa, Scianni, Miranda, and Bonatto, 2023) estimates the projected DG-installed power for 150 days. Some models, such as ARIMA, SARIMA, and Bass, make the projections. These models made predictions in several scenarios. This article compared the models, concluding that no model could be considered optimal in all scenarios; in other words, for each scenario analyzed, a model was better suited.

Only one article was found using the ARIMA model to estimate the projection of DG-installed power but over a 150-day horizon (V. B. Costa et al., 2023). Other articles using the ARIMA model in the DG area make very short-term forecasts (Jain and Mahajan 2022; Liu et al. 2022; Torres, Millan, Gonzales, and Lopez 2019).

This article evaluates the feasibility of applying an ARIMA model performing long-term forecasts of DG-installed power. For this, it will have as a reference for comparison the (EPE, 2024) that uses the Bass diffusion methodology. The evaluation of models for forecasts with this period is important for the energy sector, where annual analyses are carried out with this horizon, as an example of the EPE's ten-year plans. In this context, this article begins the study of an important gap in the literature.

This article uses Eviews7 software to choose the model and make predictions. In this software, the characteristics of the time series are evaluated, the best model is chosen based on the indices indicated in the literature, and the DG-installed power forecast over ten years is made. The study entry parameters from (EPE, 2024) are compared with the ARIMA model used in this article. Finally, the DG-installed power forecast curves are compared.

This article is organized into five sections. The first section is the introduction, which situates the reader, contextualizes the theme, and presents the article's objective. The second section presents a theoretical framework of the two methodologies analyzed in this article. The third section presents the methodology for forecasting and comparisons. The fourth section presents the results and discussions. The fifth section makes the final considerations of the article.

## 2 Referential theoretical

Several methodologies are used to make forecasts in the electricity sector. The paper (Vom Scheidt et al., 2020) shows that ARIMA models, gray models, SVRs, and RNA are the most widely used to make long-term predictions for electrical systems. The Support Vector Regression (SVR) and Artificial Neural Networks (ANN) models are machine learning-based models, and the gray and ARIMA models are traditional models for time series. Combinations of these models were used to make forecasts for the electricity sector. Among the models used to make forecasts in the electricity sector, the Bass model has shown greater recurrence for the DG-installed power forecast. Methodologies using this model were found in some articles in the development of this research (V. Costa et al., 2022; V. B. Costa et al., 2022; Da Silva et al., 2020; Islam, 2014; Radomes Jr and Arango, 2015). This section will introduce the ARIMA model and the Bass model.

### 2.1 Bass Model (Diffusion Theory)

The Bass model is a mathematical framework that describes the diffusion process of new technologies in the market. Distributed Generation (DG) in Brazil is a new technology, making it suitable for forecasting studies using the Bass model (Islam, 2014). In Brazil, the Energy Research Company (EPE) employs this model to project DG-installed power (EPE. 2022).

Bass model describes the diffusion of innovations over time. According to (Rogers, 2003), the curve that expresses the new technologies adoption over time is like an "S" curve, where, at first, the adoption is very slow, followed by accelerated growth and stagnation. The Bass model formulation is described by

$$f(t) = (p_i\pi + q_iF(t))(1 - F(t)), \quad (1)$$

where  $f(t)$  is the adoption probability at time  $t$ ,  $F(t)$  is the cumulative distribution of the adoption probability,  $p_i$  is the innovation coefficient, which represents the external influence on the diffusion process, and  $q_i$  is the imitation coefficient, which represents the internal influence on the diffusion process.

Equation 1 presents the Bass model in its "pure" form. With this formulation, it is impossible to forecast the potential market from real data. It was necessary to use the Bass model in its closed form, according to Equation 2, to insert real data.

$$F(t) = 1 + \frac{1 - e^{-(p_i + q_i)t}}{1 + \frac{q_i}{p_i} e^{-(p_i + q_i)t}}, \quad (2)$$

where real data can be incorporated to estimate the parameters (EPE. 2022). The number of new adopters distributed over time can be calculated using.

$$N(t) = mF(t), \quad (3)$$

where  $N(t)$  represents the cumulative number of adopters at time  $t$ , and  $m$  is the potential market (the number of consumers who will adopt the technology, giving sufficient time for dissemination).

### 2.2 ARIMA model for time series forecasting

According to (Morettin and Toloi, 2004), time series are analyzed to investigate the generating mechanism, describe its behaviour, look for relevant periodicities, and make predictions of values. Several models, such as AR, MA, ARMA, and ARIMA, can analyze these.

The ARIMA model is widely used to make predictions of future data, and the article (vom Scheidt et al., 2020) reviews the various studies published with this focus. The article shows that several studies have used the ARIMA model to make predictions in the electricity sector. This model integrates the autoregressive (AR) and moving average (MA) models. It can be appropriate for non-stationary series, which is the time series case in the electricity sector. In practice, if through  $n$  differences of a non-stationary time series, to transform it into a stationary series, the ARIMA model can be used (Morettin and Toloi, 2004). The ARIMA model can be denoted as ARIMA (p,d,q), and mathematically describes as

$$d_t = \mu + \sum_{i=1}^p \alpha_i d_{t-1} + \sum_{i=1}^q \beta_i \varepsilon_{t-1} + \varepsilon_t, \quad d_{t=\Delta} d_{y_t} \quad (4)$$

where  $d_t$  is the transformed variable based on the differentiation,  $\mu$  is the constant parameter,  $p$  is the order of the AR component,  $\alpha_i$  are parameters of the AR component,  $q$  is the order of the MA component,  $\beta_i$  are parameters of the MA component,  $\varepsilon_t$  is the error,  $d_t$  is the order of the integrated, and  $y_t$  is the variable of interest (V. B. Costa et al., 2023).

The methodology for identifying the best models for making predictions from a given time series is iterative. At the identification stage, one or more models can be chosen, and the choice can be made based on autocorrelations, partial correlations, and the Dickey and Fuller test. The Dickey and Fuller test is used to identify whether a time series is stationary. This test also helps transform the time series into stationary when necessary. The correlograms of autocorrelations and partial correlations estimated by the differentiated series are analyzed to determine the AR and MA components. Finally, the Akaike and Schwarz criteria are evaluated to define one or more appropriate models, and the lowest values correspond to the most satisfactory models. Residue diagnostics are also used to assess the models. It helps adjust the model through an iterative process. The process of identifying the model and predicting time series can be carried out with the help of software such as MINITAB, SCA, and EVIEWS (Morettin and Toloi, 2004).

### 3 Methodology

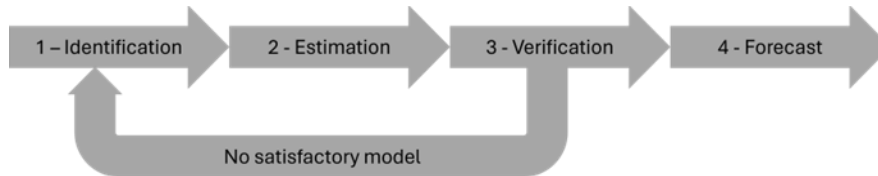
The Bass model was used as a benchmark to evaluate the ARIMA model's long-term predictions of DG-installed power. This methodology section presents the step-by-step process for achieving results.

The monthly DG-installed power time series dataset was obtained from ANEEL's open database (ANEEL, 2024). The database provided information on all approved DG systems up to the data export time. The time series used in this article was developed by adding the monthly power from January 2014 to December 2023. This coincides with the period analyzed by the EPE in (EPE, 2022).

The results of this article were compared with the projections made by EPE, incorporating information that EPE considered in its report. It was possible to associate information on changes in DG rules provided for by Law 14,300 of 2022. These changes are directly related to the reduction in the number of installations, as they have reduced the benefits of new entrants to the sector. Given the importance of this information, it was incorporated into the series from January 2023, the date on which its rules came into effect. It was not possible to associate more information due to the limitations of the model and software used.

The E-views 7 software was used to make the growth forecasts of the monthly power curve installed by the DG and identify the best model. E-views 7 allows us to make projections using various models, such as ARIMA. The software carried out some steps to achieve the DG's monthly installed capacity forecast by December 2032, coinciding with the forecasts in the EPE report. This article organized the

methodology for forecasting the installed capacity DG in stages. These steps were based on the Box and Jenkins methodology, which finds the best model to perform time series forecasts with the ARIMA model (Box, Jenkins, and Reinsel, 2008). Figure 1 shows the iterative flow from stages to prediction.



**Figure 1:** Flow of steps to choose the model and forecast the installed power based on the Box and Jenkins methodology.

Stage 1 (Identification) had the main objective to identify possible models. This stage consisted of observing the behaviour of the series and verifying trends, seasonality, and stationarity. The series graph, the correlograms, and the Augmented Dickey-Fuller (ADF) statistical test were used, all generated in the software. This process showed that it was a non-stationary series. Next, the first difference of the time series was made, making it stationary in the first difference, confirmed by correlograms and the ADF statistical test. Through this step, it can be concluded that ARIMA models could be used. In stage 2 (Estimation), the parameters (p, q, d) presented in subsection 2.2 were estimated, observing the autocorrelation and partial correlation correlators generated by the series in the first difference. Step 3 (Verification) consists of checking and cleaning up the residue generated by the models estimated in the previous step. The model with the highest  $R^2$  index and the lowest Akaike and Schwarz indexes was chosen in this stage. These three steps were repeated until a satisfactory model was reached. Once the model is defined, the prediction can be made.

The ARIMA and Bass diffusion models were compared from two points of view: the methodological characteristics and their predictions. The comparison of the forecasts consisted of making a graph plotting the annual DG-installed powers predicted by the ARIMA model and the Bass model predictions presented in (EPE, 2024). A table was set up with the percentage differences between the ARIMA and the Bass model predictions to assist in the analysis of the forecasts. The comparison of the methodological characteristics consisted of comparing the inputs used for the ARIMA model with the inputs presented in (EPE, 2022).

## 4 Results and discussions

Firstly, the methodological characteristics of the ARIMA model development were evaluated. Table 1 presents the inputs that each methodology used. The ARIMA model has the main input, the time series of DG-installed power. In the model by EPE, this time series was used to calculate the average DG-installed power in Brazil since its forecast was based on the number of DG installations. In addition, the time series was used to calibrate the parameters of innovation and imitation in the Bass model, utilizing a nonlinear regression.

Law 14,300 was incorporated into the historical series from January 2023, when its rules were implemented. The statistical tests showed a negative significance of this parameter, which was already expected since the impacts of the new Law coincide with a sharp drop in the monthly DG-installed power. This information was also used in the EPE model, but its data was used to calculate the new financial indicators of DG systems.

The other inputs presented in Table 1 were used only by the EPE model. The payback was calculated considering the different distributors, as the values of the tariffs are different. Additionally, consumers

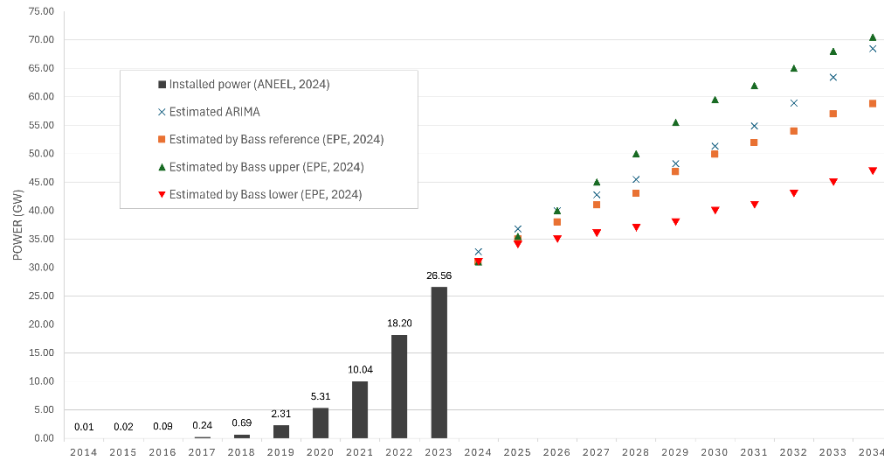
have been segmented by type, such as residential and commercial consumers. Socioeconomic factors were also considered, such as the income of the consumer unit and space for installing the system. These last two inputs were used to estimate the change in market size over time. These inputs are utilized to predict the potential market for new adopters.

Input	EPE model	ARIMA model
Time Series of Installed Load	x	x
Period of validity of Law 14.300	x	x
Energy Distributor	x	
Type of consumer	x	
Socioeconomic factors	x	
Payback	x	

**Table 1:** Comparison between the main inputs of the ARIMA and Bass models

As can be seen, the model used by the EPE considered several parameters that the ARIMA model did not. This difference is related to the methodologies used. While the Bass model can impute several market data to calculate its diffusion, the ARIMA model had the correlations of its time series as its main reference.

Figure 2 presents four DG-installed power forecasts, three of which were extracted from the PDE34 (EPE, 2024), and one is the projection estimated by the ARIMA model. EPE made DG-installed power forecasts for three scenarios: the upper one considers a 1-to-1 compensation system, case before Law 14,300; the reference scenario considers that distribution costs will not be compensated; and the lower scenario assumes that only the cost related to power generation will be offset by the DG system. The forecasts presented similar curve profiles, indicating that market growth is slowing down but with different intensities.



**Figure 2:** Forecast of the DG-installed power of the ARIMA model and the Bass model extracted from (EPE, 2024).

The most significant difference between the predictions occurred between the ARIMA models and the Bass model in the lower scenario. Table 2 shows the percentage differences between the estimates. Comparing the ARIMA model with the result of the lower scenario, it is noted that the differences begin to vary from 2025 onwards, reaching differences close to 30%.

The DG-installed power forecast in the reference scenario was close to the estimates made by the ARIMA model. The differences were around 5% until 2032, the year that the difference increased, reaching 14% in the last projected year. The reference scenario considers compensation conditions very close to the current reality, which may explain the scenario of greater convergence, given that these are the main information the ARIMA model considers.

The estimates of the upper scenario showed deviations similar to those of the reference scenario, with an average difference of 6%. However, the estimates of this scenario showed more significant variability in the differences between the models. From 2024 to 2027, the differences are around 5%; between 2028 and 2032, the differences jump to an average of 13%, then the differences are reduced.

% deviation for ARIMA	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
Reference	5%	5%	5%	4%	5%	3%	3%	5%	8%	10%	14%
Upper	5%	4%	0%	-5%	-10%	-15%	-16%	-13%	-10%	-7%	-3%
Lower	5%	8%	12%	16%	19%	21%	22%	25%	27%	29%	31%

**Table 2:** Percentage differences between the estimates made by the ARIMA model and the predictions made by the Bass model.

Based on these comparisons, the ARIMA model has the potential to be used to predict DG-installed power in this 10-year horizon, especially when considering that the future scenario is similar to the current one.

The Bass model demonstrated some advantages over the ARIMA model. One is the possibility of adding various market information, allowing the creation of scenarios to make predictions. The Bass model's versatility benefits those planning the sector, allowing them to test various scenarios. However, the ARIMA model can be combined with other methodologies, as presented in subsection 2.2.

Combinations of the ARIMA model with other models can deliver more versatile results, seeking to create scenarios such as those presented in this article.

## 5 Conclusions

This study evaluated the application of an ARIMA model for long-term forecasts of DG-installed power. An ARIMA model was developed and applied to forecast the DG-installed power from 2024 to 2034. The evaluation used the Bass diffusion model applied in the PDE34 as a benchmark.

The results highlighted the differences between the methodologies, especially regarding inputs. It was observed that the methodology that used the Bass model was able to incorporate several socioeconomic indicators, while the ARIMA model did not allow this.

The forecasts resulted in similar curves, showing a drop in the growth rate. The forecasting of the ARIMA model was very similar to the forecast estimated by one of the scenarios presented by EPE. The results demonstrated that the ARIMA model has the potential to make accurate predictions, particularly when the boundary conditions are similar to those of the historical time series. However, the ARIMA model had limitations regarding the creation of scenarios. The methodology used did not allow the introduction of additional information into the model to create alternative scenarios.

Although the ARIMA model has some limitations compared to the Bass model, it has demonstrated significant potential for application. This conclusion represents an important contribution to the literature since no previous studies have used the ARIMA model for long-term DG predictions. This article begins the validation of an alternative model for DG market forecasting.

With some modifications in the methodology, the ARIMA model can overcome the limitations pointed out in this article. As a suggestion for future research, some changes are recommended: the ARIMA model used in this article could be combined with other approaches, incorporating additional indicators to improve the model. Incorporating indicators such as payback and other relevant parameters can improve the model to estimate forecasts in various scenarios. The segmentation of prosumers could also improve results since they have different financial indicators, resulting in DG's different growth rates. Incorporating this information into the ARIMA model can enhance its versatility, making it a viable alternative for forecasting in the DG sector.

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# Evaluation of Photovoltaic Performance in DSSCs Through Fe<sub>2</sub>O<sub>3</sub> Doping in TiO<sub>2</sub> Electrodes Sensitized by Organic Dyes

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## Abstract

This work evaluated the photovoltaic conversion efficiency of dye-sensitized solar cells (DSSCs) by doping titanium dioxide (TiO<sub>2</sub>) anodes with varying proportions of iron oxide (Fe<sub>2</sub>O<sub>3</sub>). Natural dyes extracted from *Chrysanthemum* and *Alstroemeria* flower petals were used as sensitizers, while platinum (Pt) was employed for the photocatalytic reaction. Both electrodes were fabricated with transparent fluorine-doped tin oxide (FTO) conductors. The excitation and vibration regions of the dye properties were evaluated by FTIR and UV-Vis spectroscopic techniques. To evaluate the photovoltaic parameters, electrochemical characterizations were performed. The photovoltaic performances of *Chrysanthemum* dye-sensitized cells with 10%, 20% and 30% doping were 3.24%, 5.25% and 4.15%, respectively, and compared to 1.35% for undoped cells. Similarly, the photovoltaic conversion yields of the *Alstroemeria* sensitizer were: 3.54%, 6.32%, 5.74%, and compared to 1.74% for undoped cells. In both cases, the highest efficiency was achieving with 20% Fe<sub>2</sub>O<sub>3</sub> doping. The results demonstrate that this doping method significantly enhances the efficiency of DSSCs, yielding up to a fourfold increase compared to undoped cells. These findings are promising, highlighting the potential of DSSCs for sustainable electricity generation.

**Keywords:** Dye-sensitized solar cells, Fe<sub>2</sub>O<sub>3</sub>doping, Photovoltaic effect, Organic dyes, Renewable energy.

## 1 Introduction

Dye-sensitized solar cells (DSSCs) represent an advanced photovoltaic technology that mimics the natural process of photosynthesis, thus being a promising and sustainable alternative energy source [1]. In this configuration, a molecular dye adsorbed on a porous semiconductor, such as titanium dioxide (TiO<sub>2</sub>), absorbs sunlight and generates electron-hole pairs [1,2]. The excited electrons are injected into the semiconductor and flow through an external circuit, generating electricity [3]. The regeneration of the dye is performed by an electrolyte, which completes the cycle [1-4]. Despite the high photoactivity of TiO<sub>2</sub>, its use presents challenges due to its limited absorption of the solar spectrum [5]. Doping with elements such as Fe<sub>2</sub>O<sub>3</sub> or CuO has shown potential to broaden the visible absorption spectrum, adjust the bandgap, and reduce electron-hole

pair recombination, increasing the efficiency of DSSCs [6-8]. In view of the above, this study adopted Fe<sub>2</sub>O<sub>3</sub> as a doping element in the TiO<sub>2</sub> anode layer, making modifications to the oxidizing surface in different proportions.

## 2 Experimental

### 2.1 Materials and Methods

The anode and cathode were fabricated on conductive glass substrates coated with fluorine-doped tin oxide (FTO), purchased from Sigma Aldrich and cut to 2.5 cm × 2.5 cm. Other materials were also purchased from Sigma Aldrich, such as TiO<sub>2</sub> nanopowder (~21 nm), Fe<sub>2</sub>O<sub>3</sub> (~50 nm), (polyethylene glycol, potassium iodide, iodine salts and hexachloroplatinic acid. TEKBOND superglue was purchased from local market, Rio de Janeiro, Brazil. FTIR spectroscopy analysis of dyes extracted from *Chrysanthemum* and *Alstroemeria* was carried out using the Agilent Cary 630 FTIR spectrometer. Analysis of the absorption spectra in the UV region of the dyes extracted for this work was carried out with a SHIMADZU UV-2600i UV-Vis spectrophotometer. The TiO<sub>2</sub> and TiO<sub>2</sub>-Fe<sub>2</sub>O<sub>3</sub> photoanodes were coated using the spin coater technique, and the hexachloroplatinic acid was deposited using the dripping technique onto photocathodes and calcined in a QUIMIS muffle furnace (model Q318S25T, Brazil). - photocurrent (JV), power-voltage (PV) and electrochemical impedance spectroscopy (EIS), under illumination from the solar simulator (Ivisun® IVIUM Technologies) with 100 mW/cm<sup>2</sup> of incident power, using an IVIUM Compactstat multipotentiostat.

### 2.2 Extraction of Natural Dyes

The photosensitizers used in this work were extracted from the petals of *Chrysanthemum* and *Alstroemeria* flowers. The preparation process involved separating 10g of flower petals, which were then ground into a powder using a mortar and pestle. The powdered samples were subsequently dispersed in 100 mL of ethanol solution. Ethanol was chosen as the solvent due to its hydroxyl group, which effectively dissolves the pigments while preserving the molecular chemical characteristics of each dye [9]. To remove any undesirable particles that could interfere with the interaction between the sensitizer and the oxidizing layer, the solution was filtered using filter paper. The filtered solutions were then stored in sterilized test tubes and placed in a refrigerator for preservation.

### 2.3 Cathode Preparation

Platinum cathodes were made to act as counter electrodes. The choice of this material was based on the superior results obtained, by Gaythri et al. [10] in comparison with the conventional cathode solution manufacturing techniques. Proper preparation of this electrode is crucial, as it is at the cathode that the cell is driven by the application of negative polarity. This is due to the electrical energy transmission process in DSSCs, carried out by the interaction of a semiconductor material, an anode, a dye that acts as a photosensitizer, a redox electrolyte and, finally, a conductive counter electrode that functions as a cathode [10,11]. The photocathode preparation was carried out using a glass substrate coated with fluorine-doped SnO<sub>2</sub> (FTO thin film). This substrate was previously cleaned in a solution of distilled water and ethanol, using an ultrasonic bath model USC-1400 MERSE for 20 minutes. Drying was carried out in a model SX 1.1 STERILIFER oven at 80°C for 10 minutes. After drying, the conductivity of the substrate was measured using a multimeter,

recording resistance values in the range of 10.3  $\Omega$ /sq to 12.5  $\Omega$ /sq. The solution for manufacturing the photocathode was prepared using 5mM hexachloroplatinic ( $\text{H}_2\text{Cl}_6\text{PtH}_2\text{O}$ ) acid in ethanolic solution. The solution was applied to the electrode using the drop casting technique on conductive glass (FTO), followed by annealing in a muffle furnace at 350°C for 30 minutes. After this period, the oven was programmed to gradually reduce the temperature until it reached room temperature.

## 2.4 Anode Preparation

Before starting preparation, the beaker was properly cleaned with distilled water, sterilized with ethanol and then placed in the oven at 90°C for 10 minutes to remove possible contamination. The following chemicals were used: polyethylene glycol (0.3g),  $\text{TiO}_2$  powder (1g), mixed with an equal volume of distilled water and acetic acid, using 6 mL of each. It is important to highlight that during the handling of titanium dioxide ( $\text{TiO}_2$ ), the lights remained off to avoid unwanted oxidation. With all the mentioned chemicals added to the beaker, the solution was subjected to ultrasound for 3 hours. To carry out the doping, the procedure above was followed, with the difference that in this case, iron III oxide ( $\text{Fe}_2\text{O}_3$ ) was added, as follows:  $\text{TiO}_2$ (90%)- $\text{Fe}_2\text{O}_3$ (10%),  $\text{TiO}_2$ (80%)- $\text{Fe}_2\text{O}_3$ (20%) and  $\text{TiO}_2$ (70%)- $\text{Fe}_2\text{O}_3$ (30%). To obtain uniformity on the FTO substrate, the spin coating technique was used, with coating at 1000 RPM for 10 seconds, controlled by Arduino software. Before depositing the pastes, all FTO substrates were identified using a multimeter. To complete the construction of the photoanodes, the substrates coated with  $\text{TiO}_2$  and  $\text{TiO}_2$ - $\text{Fe}_2\text{O}_3$  were kept in the muffle furnace and annealed at 450°C for 30 minutes. The objective of annealing was to transform the  $\text{TiO}_2$  structure to the anatase phase, ensuring better absorption of photons by the semiconductor material, better transport of electrons by the semiconductor film and reduction of the cell's internal resistance.

## 2.5 Fabrication of DSSCs devices

To complete the assembly of the photovoltaic cells, the electrodes (photoanodes already coated with the natural dyes specific to each fruit and cathode) were sandwiched with a spacer in the middle and filled with redox electrolyte. The redox electrolyte was filled between them consisting of an iodine-based solution capable of aiding electron transport. Here, the electrolyte solution was prepared using 2.075g of KI, 0.12g of  $\text{I}_2$ , acetonitrile (5mL) and polyethylene glycol (0.2g). In this final assembly procedure, electrolytic injection may cause spillage outside the active area of the solar cell. When this happens, there is no efficient transport of electrons between the components of the device, and in this way, the efficiency of the device decreases. When the seal is carried out, it prevents electrolyte leakage. For this, a small amount of superglue was applied externally (not interfering with the electrochemical properties of the cells) horizontally on the two adjacent sides of one of the electrodes in a parallel manner. A small strip was left on the sides of each electrode, which served as a contact for electrochemical characterization. The schematic representation of the finished DSSC assembly is shown in Figure 1.

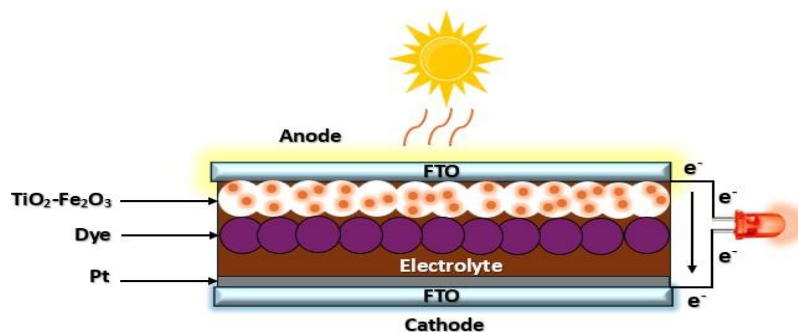


Figure 1: DSSC assembly diagram

### 3 Results and Discussion

#### 3.1 FTIR Spectroscopy

According to the infrared plots of the *Chrysanthemum* and *Alstroemeria* dyes presented in Figure 2, it was possible to analyze an intense band obtained in the spectral region between  $3100\text{ cm}^{-1}$  and  $3500\text{ cm}^{-1}$  and was due to the existence of vibrations of the hydroxyl group (O-H) present in the molecules of the dyes [12]. The peaks located between  $3000\text{ cm}^{-1}$  and  $2850\text{ cm}^{-1}$  are attributed to the symmetric and asymmetric system stretching of the vibration modes of the C-H group [13]. The peaks between  $1750\text{ cm}^{-1}$  and  $1650\text{ cm}^{-1}$  are attributed to C=C stretching vibrations of benzene and alkene rings, while the peak between  $1000\text{ cm}^{-1}$  to  $1250\text{ cm}^{-1}$  can be correlated to the stretching vibration mode of the carbonyl group (C-O) [12,13]. The carbonyl group present in dyes is capable of binding to semiconductor oxides, which facilitates the injection of electrons from the dye into the  $\text{TiO}_2$  layer.

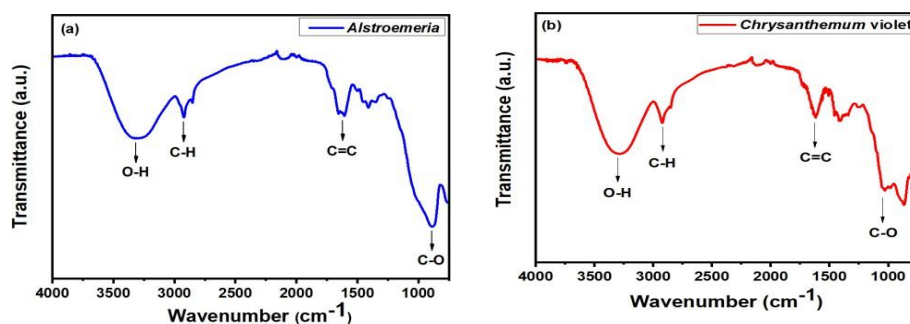
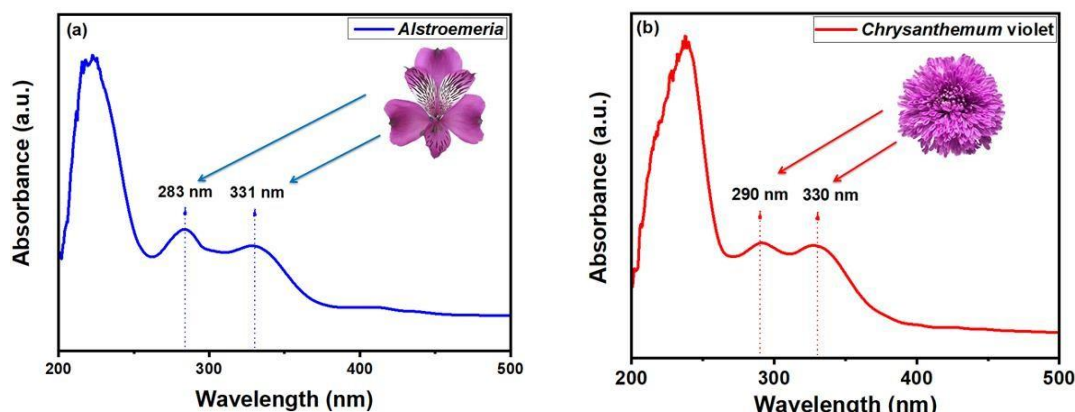


Figure 2: FTIR spectra of extracted dyes from: (a) *Alstroemeria* and (b) *Chrysanthemum* violet

### 3.2 UV-Vis Spectroscopy

The UV-Vis technique is widely used in the characterization of DSSCs due to its ability to provide detailed information about the optical properties of the materials involved, such as verifying light absorption through the dye, providing a spectrum that reveals which lengths of wave are absorbed more efficiently. Furthermore, it also provides essential information about the ground state of the dye molecule, the excited state and the range of solar energy absorbed by the active layer molecule. Figure

3 shows the UV-Vis absorption spectra of dyes extracted from the petals of *Alstroemeria* and *Chrysanthemum* flowers. A wide range of absorption spectra can be noted in the near-ultraviolet region, between 283 nm and 331 nm, corresponding to anthocyanin peaks, more specifically to the compound petunidin anthocyanin radicals [12,13].

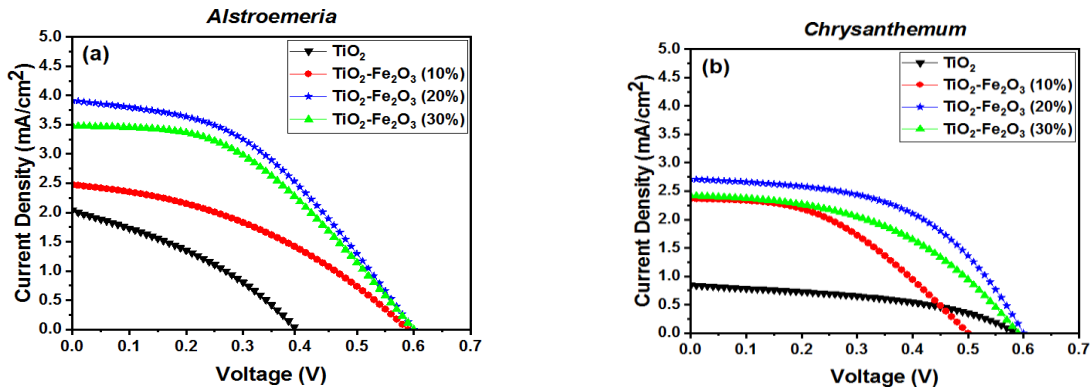


**Figure 3:** Absorption spectra of extracted dyes from (a) *Alstroemeria* and (b) *Chrysanthemum*

### 3.3 Electrochemical Characterization

The electrochemical characterization of DSSCs is essential to understand the functioning mechanisms and identify the performance limitations of these cells. Through this technique it is possible to have a detailed understanding of the internal processes of these energy generating devices, helping to develop more efficient materials and topologies, being considered essential for optimizing and improving the best photovoltaic conversion [2,12].

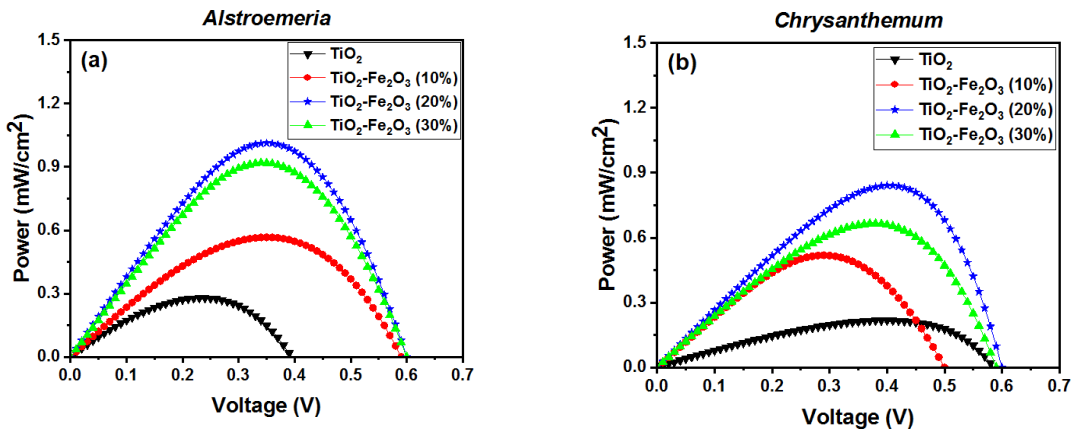
The first technique used to obtain the photovoltaic parameters was current vs voltage (I-V curve), where it consists of measuring the current generated by the cell as a function of the applied voltage, and from this, important parameters are extracted such as the short-circuit current density ( $J_{sc}$ ), open-circuit voltage ( $V_{oc}$ ), fill factor ( $FF$ ) and photovoltaic efficiency ( $\eta$ ). In order to facilitate the identification of dyes, the abbreviations Als (*Alstroemeria*) and C.V. (*Chrysanthemum violet*) were adopted. Figure 4 shows the I-V curves with the doping carried out to their respective photosensitizers.



**Figure 4:** Current density curves ( $J_{sc}$ ) with the various dopants: (a) *Alstroemeria* and (b) *Chrysanthemum*

This current density ( $J_{sc}$ ) measured in mA/cm<sup>2</sup> represents the current generated when the cell is short-circuited, reflecting the efficiency of light absorption by the dye and the separation and collection of charge carriers [13]. Through the values obtained, it was observed that there was a gain in  $J_{sc}$  in both photosensitizers (Als and C.V.), up to 20% doping (3.91 mA/cm<sup>2</sup> and 2.71 mA/cm<sup>2</sup>) and a slight decrease in 30% (3.48 mA/cm<sup>2</sup> and 2.42 mA/cm<sup>2</sup>), but this is still higher than the cases using only TiO<sub>2</sub> (2.04 mA/cm<sup>2</sup> and 0.84 mA/cm<sup>2</sup>) and 10% (2.48 mA/cm<sup>2</sup> and 2.369 mA/cm<sup>2</sup>).

In addition to the  $I$ - $V$  curve, it is also essential to evaluate the power vs voltage curve ( $P$ - $V$  curve), as this provides valuable information about the performance of the DSSC. A curve that shows a high  $V_{oc}$  and  $I_{sc}$  indicates good initial performance [14,15]. However, to maximize efficiency, the cell must operate close to the maximum power point ( $P_{max}$ ). Through Figure 5 it is possible to observe the  $P$ - $V$  curves.

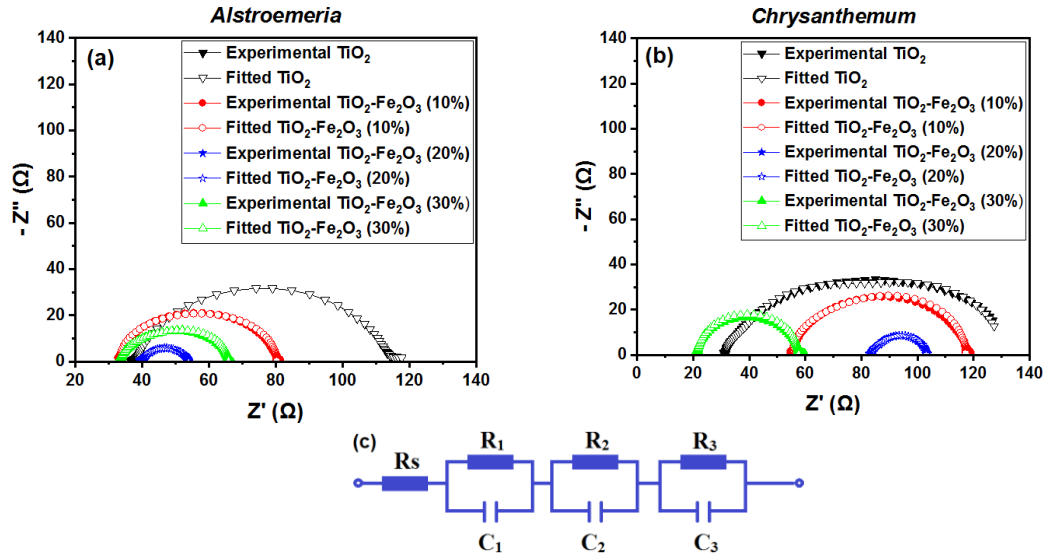


**Figure 5:**  $P$ - $V$  curve with various dopants: (a) *Alstroemeria* and (b) *Chrysanthemum*

In a similar way to the  $I$ - $V$  curves, the powers in both dyes (Als and C.V.) with the highest values were provided by the DSSCs with 20% doping (1.01 mW/cm<sup>2</sup> and 0.84 mW/cm<sup>2</sup>), having adequately followed the behavior of current density ( $J_{sc}$ ).

Below, in Figure 6 (a) and 6 (b) it is possible to observe the Electrochemical Impedance

Spectroscopy (EIS) curves in correspondence with the equivalent circuit in Figure 6 (c) and their respective values of each experimental element and plotted with their associated errors in Table 1.



**Figure 6:** EIS curve with the various dopants: (a) *Alstroemeria*, (b) *Chrysanthemum* and (c) corresponding equivalent circuit

**Table 1:** Values of each element of the equivalent circuit with their associated errors

Dyes/Semiconductor	R <sub>s</sub> (Ω)	R <sub>1</sub> (Ω)	R <sub>2</sub> (Ω)	R <sub>3</sub> (Ω)	C <sub>1</sub> (μF)	C <sub>2</sub> (μF)	C <sub>3</sub> (μF)
Als: TiO <sub>2</sub>	38.56 ±0.78	73.16 ±1.27	15.75 ±0.21	6.02 ±1.21	44.29 ±2.28	144.28 ±3.01	87.43 ±3.43
C.V.: TiO <sub>2</sub>	31.51 ±0.35	47.85 ±3.04	43.65 ±3.15	7.099 ±7.24	812 ±7.14	142.5 ±3.02	92.42 ±5.44
Als: TiO <sub>2</sub> -Fe <sub>2</sub> O <sub>3</sub> (10%)	33.18 ±0.26	24.60 ±11.36	22.44 ±12.5	8.49 ±5.93	47.30 ±18.24	18.80 ±6.41	73.49 ±6.15
C.V.: TiO <sub>2</sub> -Fe <sub>2</sub> O <sub>3</sub> (10%)	55.43 ±0.24	44.27 ±3.19	17.56 ±8.08	3.91 ±9.74	46.57 ±6.25	27.12 ±3.38	78.26 ±7.47
Als: TiO <sub>2</sub> -Fe <sub>2</sub> O <sub>3</sub> (20%)	39.29 ±0.13	2.67 ±13.20	10.20 ±3.22	1.68 ±4.46	16.19 ±23.92	10.41 ±1.79	45.36 ±7.56
C.V.: TiO <sub>2</sub> -Fe <sub>2</sub> O <sub>3</sub> (20%)	83.32 ±0.10	16.57 ±1.45	3.26 ±7.22	2.25 ±0.13	12.16 ±3.31	78.74 ±7.26	48.82 ±9.30
Als: TiO <sub>2</sub> -Fe <sub>2</sub> O <sub>3</sub> (30%)	33.67 ±0.29	22.90 ±3.30	9.20 ±8.11	7.84 ±0.29	34.07 ±6.41	19.33 ±3.56	64.46 ±13.47
C.V.: TiO <sub>2</sub> -Fe <sub>2</sub> O <sub>3</sub> (30%)	21.60 ±0.58	36.01 ±0.69	12.38 ±11.43	9.14 ±0.57	16.54 ±1.55	23.67 ±20.10	68.53 ±15.17

Through this technique, it was possible to individually evaluate the response of each DSSC to a small alternating voltage disturbance at various frequencies, identifying the internal resistances and dynamic phenomena inside the cells. In this case, the higher the impedance, the lower the electron flow capacity [16]. It was observed that the largest semicircles, both in Figure 6 (a) and in Figure 6 (b), were presented by the photoanodes without Fe<sub>2</sub>O<sub>3</sub> doping, and the smallest ones, by 20% doping, corroborating coherently with the results presented in Figures 4 and 5.

Based on the obtained data, it is possible to calculate the fill factor (*FF*), which is a measure of the quality of the solar cell that indicates the proportion of the maximum (or ideal) electrical power that the DSSC can generate in relation to the maximum theoretical power that could be generated if the cell operated at *V<sub>oc</sub>* and *J<sub>sc</sub>* simultaneously [14-16]. The *FF* is obtained as described in Equation 1.

$$FF = \frac{P_{max}}{J_{sc} \cdot V_{oc}} \quad (1)$$

In order to evaluate the solar conversion performance of each DSSC, the last photovoltaic parameter is calculated through the efficiency ( $\eta$ ), expressed by Equation 2 [17,18].

$$\eta(\%) = \frac{J_{sc} \cdot V_{oc} \cdot FF}{P_{in}} \cdot 100 \quad (2)$$

Table 2 presents the comparison of the photovoltaic parameters of DSSCs using only TiO<sub>2</sub> anodes and those doped with Fe sensitized with different natural dyes obtained in this work with those in the literature.

**Table 2:** Photovoltaic parameters using TiO<sub>2</sub> and Fe doped anodes sensitized with different natural dyes

Dyes	Anode	<i>J<sub>sc</sub></i> (mA/cm <sup>2</sup> )	<i>V<sub>oc</sub></i> (V)	<i>FF</i>	$\eta$ (%)	Ref.
<i>Annona atemoya</i>	TiO <sub>2</sub>	0.06	0.50	0.62	0.19	[14]
<i>Physalis peruviana</i>	TiO <sub>2</sub>	0.30	0.39	0.42	0.30	[14]
<i>Lantana repens</i>	TiO <sub>2</sub>	0.45	0.69	0.34	0.12	[15]
<i>Solidago canadensis</i>	TiO <sub>2</sub>	0.93	0.79	0.42	0.31	[15]
<i>Gerbera</i>	TiO <sub>2</sub>	1.22	0.59	0.53	1.54	[16]
<i>Leucanthemum</i>	TiO <sub>2</sub>	0.42	0.54	0.27	0.88	[17]
<i>Pawpaw</i>	TiO <sub>2</sub>	5.10	0.49	0.30	1.72	[18]
<i>Pawpaw</i>	TiO <sub>2</sub> -Fe <sub>3</sub> O <sub>4</sub>	6.10	0.72	0.33	3.28	[18]
<i>Ocimum gratissimum</i>	TiO <sub>2</sub>	0.07	0.26	0.36	1.70	[19]
<i>Ocimum gratissimum</i>	TiO <sub>2</sub> -FeO	0.10	0.43	0.46	4.00	[19]
THs	TiO <sub>2</sub>	3.04	0.75	0.50	1.17	[20]
THs	TiO <sub>2</sub> -FeO(25%)	7.89	0.79	0.57	3.55	[20]
THs	TiO <sub>2</sub> -FeO(50%)	2.49	0.74	0.50	0.92	[20]
<i>Alpinia purpurata</i>	TiO <sub>2</sub>	0.49	0.53	0.40	0.65	[13]
<i>Alstroemeria</i>	TiO <sub>2</sub>	2.04	0.39	0.29	1.74	[13]
<i>Chrysanthemum violet</i>	TiO <sub>2</sub>	0.85	0.58	0.44	1.35	[12]
<i>Alstroemeria</i>	TiO <sub>2</sub> -Fe <sub>2</sub> O <sub>3</sub> (10%)	2.48	0.59	0.39	3.54	[this work]
<i>Chrysanthemum violet</i>	TiO <sub>2</sub> -Fe <sub>2</sub> O <sub>3</sub> (10%)	2.37	0.50	0.44	3.24	[this work]
<i>Alstroemeria</i>	TiO <sub>2</sub> -Fe <sub>2</sub> O <sub>3</sub> (20%)	3.91	0.60	0.43	6.33	[this work]
<i>Chrysanthemum violet</i>	TiO <sub>2</sub> -Fe <sub>2</sub> O <sub>3</sub> (20%)	2.71	0.60	0.52	5.25	[this work]
<i>Alstroemeria</i>	TiO <sub>2</sub> -Fe <sub>2</sub> O <sub>3</sub> (30%)	3.48	0.60	0.44	5.74	[this work]
<i>Chrysanthemum violet</i>	TiO <sub>2</sub> -Fe <sub>2</sub> O <sub>3</sub> (30%)	2.42	0.59	0.46	4.15	[this work]

## 4 Conclusions

This study investigated the photovoltaic performance of dye-sensitized solar cells by doping iron oxide ( $\text{Fe}_2\text{O}_3$ ) in different proportions in photoanodes composed of titanium dioxide ( $\text{TiO}_2$ ) layers. For this analysis, natural photosensitizers extracted from *Alstroemeria* (Als) and *Chrysanthemum* violet (C.V.) were used. It was observed that both dyes reached the highest power values with the doping of 20%  $\text{Fe}_2\text{O}_3$  (Als: 1.01  $\text{mW}/\text{cm}^2$  and C.V.: 0.84  $\text{mW}/\text{cm}^2$ ), and the best efficiencies were obtained, with emphasis on the Als dye, which reached a maximum efficiency of 6.33%. Concerning the electrochemical analyses, all the cell devices doped with  $\text{Fe}_2\text{O}_3$  presented an increase in solar energy conversion compared to the cells that used only  $\text{TiO}_2$  as the oxidizing material. Furthermore, it was found that, although doping increases the solar spectrum utilization capacity, a performance saturation occurs around 30% doping. This phenomenon is attributed to the wider visible light absorption bandwidth of  $\text{Fe}_2\text{O}_3$  compared to pure  $\text{TiO}_2$ . The best electron generation was obtained when  $\text{TiO}_2$  is doped with  $\text{Fe}_2\text{O}_3$ , increasing the light absorption in the visible spectrum. Therefore, doping with  $\text{Fe}_2\text{O}_3$ , also contributes to the reduction of electron-hole pair recombination, promoting more efficient charge separation and better interaction between the dye and the oxidizing surface. In summary, we successfully demonstrate that the  $\text{Fe}_2\text{O}_3$  doping method was considerably effective in improving a better DSSCs efficiencies, increasing at least four times the value compared to the undoped cells. The promising results obtained with the DSSCs constructed in this work suggest a great potential for generating electricity in a sustainable manner.

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# Systematic Literature Review of Low-Carbon Hydrogen: Encompassing EESG Perspectives

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## Abstract

This study aims to conduct a systematic literature review and a comprehensive bibliometric analysis of the low-carbon hydrogen production chain, addressing the economic, social, environmental, and governance (EESG) dimensions. The analysis identified key trends, gaps, and scientific contributions in the field, as well as mapped the evolution of related topics. The results of the bibliometric analysis reveal a complex network of international collaborations, highlighting countries such as the United States, China, Germany, the United Kingdom, and Japan as leaders in low-carbon hydrogen research. Additionally, a predominant focus on the environmental and economic dimensions was identified, while the social and governance dimensions were underestimated. The systematic review revealed that most of the research is concentrated on the hydrogen production phase, with less attention given to the stages of storage, distribution, and consumption. Based on the findings, the study proposes recommendations for the sustainable development of the sector, emphasizing the need for a more balanced approach that integrates all EESG dimensions. It concludes that, for the long-term success of the low-carbon hydrogen transition, not only technical efficiency and economic viability are essential, but also social acceptance and robust governance policies. This study provides a solid foundation for future research and policy formulation, contributing to a cleaner and more sustainable energy future.

Keywords: Low-Carbon Hydrogen; EESG; Systematic Literature Review; Sustainable development.

## 1 Introduction

The global energy transition has been widely discussed in recent years, focusing on the urgent need to reduce carbon emissions and mitigate the impacts of climate change (Kabeyi and Olanrewaju 2022). In this context, low-carbon hydrogen emerges as a promising solution, offering significant potential to decarbonize various sectors, including transportation, industry, and power generation (Oliveira, Beswick and Yan 2021). For low-carbon hydrogen to be effectively integrated into the global energy system, key challenges must be addressed, and a comprehensive understanding of its production chain, as well as the Environmental, Economic, Social, and Governance (EESG) dimensions involved, are necessary (Zavarkó, 2023).

Currently, the incorporation of EESG criteria in the production of low-carbon hydrogen is essential to ensure long-term sustainability and viability. Recent research highlights the importance of adopting

EESG principles to increase transparency, foster stakeholder trust, and promote sustainable practices throughout the hydrogen value chain. Studies show that low-carbon hydrogen, produced via renewable energy sources, can significantly reduce greenhouse gas emissions and contribute to the decarbonization of various industries (Oliveira, Beswick and Yan 2021). Additionally, the inclusion of social aspects, such as community engagement and equitable job creation, along with robust governance frameworks, ensures that the hydrogen economy develops in a way that benefits all stakeholders and supports global climate goals (Zavarkó 2023).

The global energy matrix based on fossil fuels is limited by its inherent inefficiencies and environmental drawbacks, significantly hindering efforts to reduce carbon emissions (Hou, Lu, and Liu 2023). The reliance on non-renewable energy sources, such as coal, oil, and natural gas, not only contributes to greenhouse gas emissions but also exacerbates climate change and environmental degradation (Wen *et al.* 2021). This dependency creates a pressing need for a transition to sustainable and renewable energy alternatives to achieve long-term climate goals and ensure a cleaner and more resilient energy future (Lv, 2023).

In the current literature, the production of low-carbon hydrogen is extensively studied, particularly in relation to its potential to contribute to the global energy transition. However, many studies tend to examine the economic, social, environmental, and governance (EESG) dimensions in isolation, without adequately integrating these aspects into a comprehensive framework. This study addresses this gap by providing a detailed analysis that incorporates all EESG dimensions, thereby offering a holistic perspective on the state of low-carbon hydrogen production. Through a systematic literature review and bibliometric analysis, this research identifies not only the trends and significant scientific contributions but also the existing gaps in the field. While systematic literature reviews are often utilized to understand the current state of research (Zhou, 2022), this study goes further by combining it with a bibliometric analysis, which reveals the geographical distribution of research, institutional collaborations, and the key players involved (Donthu *et al.*, 2021). This integrated approach contributes to a more complete understanding of the challenges and opportunities associated with low-carbon hydrogen, thus providing a solid foundation for future research and policy-making in this critical area.

The purpose of this paper is to conduct a systematic literature review and a bibliometric analysis of the low-carbon hydrogen production chain, focusing on EESG dimensions. The study aims to identify trends, gaps, and scientific contributions in the field, as well as to propose recommendations for the sustainable development of the sector. By addressing the challenges and opportunities for the global energy transition, this research underscores the importance of integrated policies and a holistic approach to promote the adoption and scalability of low-carbon hydrogen. Ultimately, this study seeks to provide a solid foundation for researchers, policymakers, and stakeholders, contributing to a cleaner and more sustainable energy future.

## 2 Methods

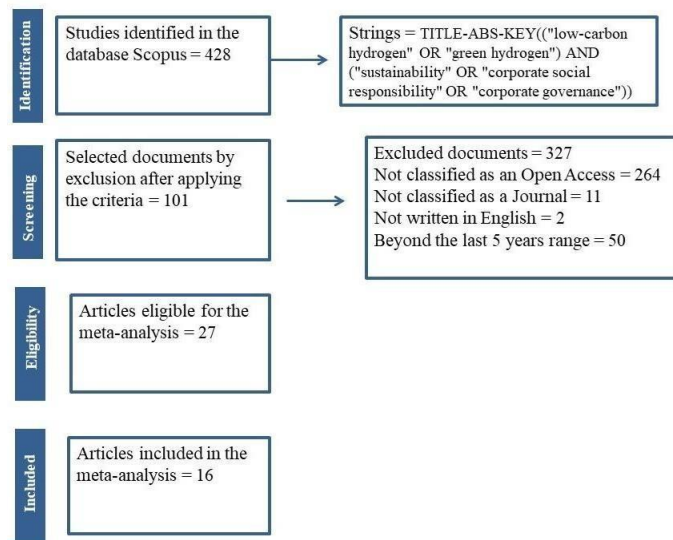
The analysis presented in this paper was conducted using a search in the Scopus database with the following string: ("low-carbon hydrogen" OR "green hydrogen") AND ("sustainability" OR "corporate social responsibility" OR "corporate governance"). Scopus was chosen for its relevance and comprehensive coverage in high-impact journals. The search yielded 428 documents, which were

refined by applying filters to select only English-language articles published between 2019 and 2023, available as open access, resulting in 101 articles.

A combined bibliometric and systematic review approach was employed to provide an in-depth analysis of the management of the low-carbon hydrogen production chain, focusing on economic, social, environmental, and governance dimensions. The bibliometric review, conducted using Bibliometrix software, mapped trends and gaps based on the co-occurrence of author keywords, following the approach recommended by Donthu *et al.*, (2021). Additionally, a systematic literature review was conducted using the PRISMA method (Zhou, 2022), ensuring transparency in the review process.

This method, which includes identification, screening, eligibility, and inclusion phases, ultimately included 16 articles in the meta-analysis. The systematic review provided qualitative support by identifying specific gaps in the literature. Based on the collected data, key questions were formulated for qualitative analysis:

- 1) At which stage of the hydrogen production chain does the study focus?
- 2) Which EESG dimensions (economic, social, environmental, governance) are addressed in the study?
- 3) What are the main impacts of the EESG dimensions?



**Figure 1:** PRISMA Flow Diagram – Screening

### 3 Results and Discussion

The presentation and discussion of the results are divided into three subtopics to address each methodological approach in more detail. Firstly, section 3.1 will discuss the results of the bibliometric study to identify critical points and gaps in the literature, presenting the co-occurrence of author keywords. Subsequently, section 3.2 will focus on the systematic review, presenting the developed flowchart and a detailed analysis of the selected articles, including the PRISMA meta-analysis.

### 3.1 Co-occurrence of author keywords

As illustrated in the Fig. 2, the results of this bibliometric analysis reveal a complex network of collaborations in the field of low-carbon hydrogen. The most cited words, such as "green hydrogen", "sustainability," "energy transition," "carbon capture and storage," and "renewable energies," reflect the current research focus on sustainable hydrogen production methods and its crucial role in the global energy transition (Weidner, Tulus and Guillén-Gosálbez, 2023; Bairrão *et al.*, 2023; Gorji, 2023).

Among the most active countries in low-carbon hydrogen research are the United States, China, Germany, the United Kingdom, and Japan, distinguished by a large number of publications and international collaborations, indicating their leadership and investment in sustainable hydrogen Technologies (Edwards, Howe and Font-Palma, 2022; Sgarbossa *et al.*, 2023; Lau and Tsai, 2022).

The presence of multiple co-authorship clusters suggests the existence of several subareas of research within the field, with each cluster representing a research community focused on specific aspects such as production methods, environmental impacts, and governance policies (Nurdiawati and Urban, 2022; Song *et al.*, 2022; Butturi and Gamberini, 2022). This analysis also highlights the importance of international collaboration networks in promoting scientific and technological advancements in the area (Fazioli and Pantaleone, 2021; Dillman and Heinonem, 2023).

When compared to bibliometric studies of other emerging fields, the co-occurrence analysis of authors in the field of low-carbon hydrogen shows a well-established collaboration network but also identifies gaps. While some areas, such as hydrogen production and storage, are well represented, others, such as social integration and governance, still require more attention and collaboration (Blohm and Dettner, 2023; Chenic *et al.*, 2022). In comparison to renewable energy, where international collaboration is more pronounced, low-carbon hydrogen research can still benefit from greater global cooperation to accelerate the development and implementation of sustainable technologies (Sgarbossa *et al.*, 2023).

The analysis identified several gaps in the current research, including the need for more studies on the social and governance impacts of hydrogen production, the insufficiency of research focused on the application of hydrogen technologies in different industrial sectors, and the lack of integrated approaches that consider environmental, economic, social, and governance impacts in a holistic manner (Masip Macía *et al.*, 2021).

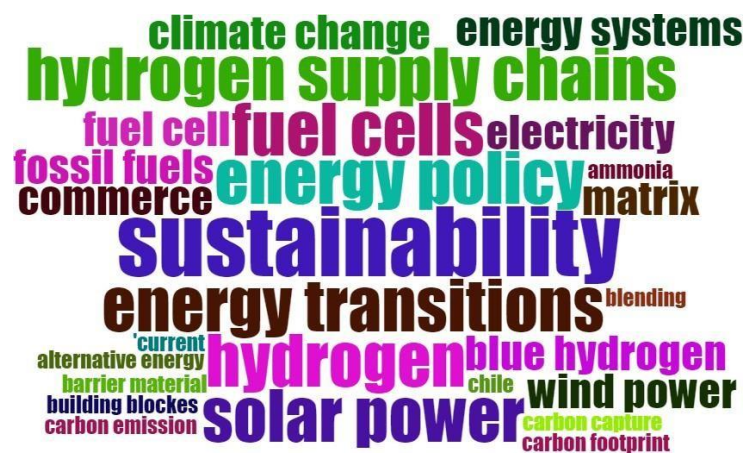


Figure 2: Co-occurrence of author keywords (Created using the Bibliometrix software).

### 3.2 PRISMA meta-analysis

Table 1, presents the PRISMA meta-analysis considering article title, keywords, stage of hydrogen production chain, EESG dimensions addressed and main EESG impacts.

Article Title	Keywords	Stage of Hydrogen Production Chain	EESG Dimensions Addressed	Main EESG Impacts
A decarbonization Roadmap for Taiwan and Its Energy Policy Implications	Taiwan; decarbonization roadmap; energy transition; carbon capture and storage; renewable energies.	Production	Environmental	Energy & Carbon Cycle
Accelerating sustainability transitions: the case of the hydrogen agenda in the North West region of England	Decarbonization; hydrogen; sustainability; policy; transition	Hydrogen production; Hydrogen storage; Hydrogen distribution; Carbon capture and storage (CCS) technologies.	Environmental	Pollution Risks & Safety
Challenges and opportunities in green hydrogen supply chain through metaheuristic optimization	consumption, green hydrogen, metaheuristic optimization, production, storage, transportation.	production; storage; transportation; consumption.	Economic; Social; Environmental; Governance.	Energy & Carbon Cycle
Decarbonising the refinery sector: A socio-technical analysis of advanced biofuels, green hydrogen and carbon capture and storage developments in Sweden	Industrial decarbonisation; Sustainability transition; Innovation system; CCS; Hydrogen; Biofuel.	Production	Economic; Social; Environmental; Governance.	Pollution Risks & Safety
Deep decarbonization of the Indian economy: 2050 prospects for wind, solar, and green hydrogen	Deep decarbonization; Indian economy; Wind energy; Solar energy Green hydrogen.	Power Generation Sector, Industrial Sector, and Transport Sector.	Environmental; Economic.	Energy & Carbon Cycle

Article Title	Keywords	Stage of Hydrogen Production Chain	EESG Dimensions Addressed	Main EESG Impacts
Energy Decarbonization via Green H2 or NH3?	Decarbonization; Green Hydrogen (H2); Green Ammonia (NH3); Renewable Energy; Energy Storage.	Production	Economic	Value Added & Decouple Growth
Environmental sustainability assessment of large-scale hydrogen production using prospective life cycle analysis	Hydrogen economy; Absolute environmental; sustainability; Green hydrogen.	Production	Environmental	Energy & Carbon Cycle and Pollution Risks & Safety
Green Hydrogen and Energy Transition: Current State and Prospects in Portugal	carbon footprint; electrolysis; green hydrogen; renewable energy; sustainability.	Production	Environmental	Energy & Carbon Cycle
Green hydrogen production: Integrating environmental and social criteria to ensure sustainability	Green hydrogen; Just transition Measurable criteria; Social sustainability; Sustainability criteria.	Production	Social	Jobs; Human Rights; Skills & Labour Standards.
Green Hydrogen Value Chain in the Sustainability for Port Operations: Case Study in the Region of Valparaiso, Chile	green hydrogen; chain value; port operations; renewable energy.	Final consumption	Environmental	Pollution Risks; Carbon Cycle; Energy; Resources; Safety; Policy Commitment & Engagement.
Logical Analysis on the Strategy for a Sustainable Transition of the World to Green Energy—2050. Smart Cities and Villages Coupled to Renewable Energy Sources with Low Carbon Footprint	Climate neutrality; fossil fuels; global warming; greenhouse gases; wind and solar photovoltaic energy; CCUS: carbon capture, use and storage.	Production	Environmental	Pollution Risks; Carbon Cycle; Jobs; Skills; Value Added; Trade; Policy Commitment & Engagement.
Macroeconomic Factors Influencing Public Policy Strategies for Blue and Green Hydrogen	Blue hydrogen; green hydrogen; carbon capture; sustainability; energy transition	Formulation of Public Policies and Strategies.	Economic	Infrastructure & Public Finance; Pollution Risks; Carbon Cycle; Stability; Regulatory Quality.

Article Title	Keywords	Stage of Hydrogen Production Chain	EESG Dimensions Addressed	Main EESG Impacts
Renewable hydrogen supply chains: A planning matrix and an agenda for future research	Renewable hydrogen supply chain; Green hydrogen; Supply chain management; Supply chain planning; Literature review.	Supply of raw materials, production, storage, distribution, and final applications.	Economic	Value Added; Jobs; Pollution Risks; Policy Commitment.
Reprint of: Renewable hydrogen supply chains: A planning matrix and an agenda for future research	Renewable hydrogen supply chain; Green hydrogen; Supply chain management; Supply chain planning; Literature review.	Production	Economic	Value Added; Jobs; Pollution Risks; Policy Commitment.
The potential of hydrogen technologies for low-carbon mobility in the urban-industrial symbiosis approach	Climate change mitigation; green hydrogen; sustainable mobility; symbiosis; urban-industrial.	Production and storage	Environmental	Value Added; Pollution Risks; Policy Commitment; Health & Safety.
Towards a Safe Hydrogen Economy: An Absolute Climate Sustainability Assessment of Hydrogen Production	Hydrogen economy; absolute sustainability; safe operating space; hydrogen policy; hydrogen certification.	Production	Economic	Public Finance; Human Rights; Pollution Risks; Stability; Regulatory Quality.

**Table 1:** PRISMA meta-analysis

The following sections address each question separately to complement the bibliometric analysis.

**1. At which stage of the hydrogen production chain does the study focus?**

The analysis of the studies revealed that most research is focused on the hydrogen production phase. Among the 16 articles included in the meta-analysis, the vast majority directly address hydrogen production. Other stages of the production chain, such as storage, distribution, and consumption, are less frequently addressed. Some studies cover multiple phases, including production, storage, and transportation, offering a more comprehensive view of the hydrogen value chain.

**2. Which EESG dimensions (environmental, economic, social, governance) are addressed in the study?**

The analyzed studies address various combinations of EESG dimensions, with a significant focus on the environmental dimension. The environmental dimension is the most prevalent, appearing in almost all studies. The economic dimension is also widely addressed, highlighting the importance of assessing the economic impacts of low-carbon hydrogen production.

The social dimension is less frequently addressed but still present in studies that emphasize social criteria such as job creation and human rights. The governance dimension is discussed in articles that address policies and regulations, underscoring the importance of a robust regulatory framework for the sector's sustainability.

**3. What are the main impacts of the EESG dimensions?**

Considering the EESG indicators, the information analyzed to answer these questions included:

In the environmental dimension, the most highlighted impacts include the reduction of greenhouse gas emissions and the mitigation of pollution risks. Studies frequently emphasize how low-carbon hydrogen production can significantly lower the overall carbon footprint and contribute to achieving climate targets. Additionally, the reduction of pollutants and the promotion of cleaner air quality are critical environmental benefits noted across the literature.

In the economic dimension, the studies often highlight the creation of added value and the possibility of decoupling economic growth from carbon emissions. The economic indicators also point to the development of new industries and markets, fostering innovation and competitiveness. Infrastructure development and public financing are other relevant economic impacts, with significant investments required to build and maintain the necessary facilities for hydrogen production, storage, and distribution.

The social dimension, although less frequently addressed, reveals significant impacts in terms of job creation, skill development, and labor standards. The studies indicate that low-carbon hydrogen production can generate new employment opportunities, particularly in regions transitioning away from fossil fuels. Furthermore, there is an emphasis on developing a skilled workforce and ensuring that job quality and labor rights are maintained. Social inclusion and community participation are also

mentioned, highlighting the importance of engaging local communities and ensuring that the benefits of hydrogen projects are widely shared.

Finally, the governance dimension presents impacts related to regulatory quality and policy stability, which are fundamental for the sustainable development of the low-carbon hydrogen sector. The studies emphasize the need for a robust regulatory framework and integrated policies to promote the adoption and scalability of low-carbon hydrogen. Effective governance ensures that environmental standards are met, economic benefits are maximized, and social impacts are managed equitably. It also provides the stability and predictability necessary for long-term investments in the hydrogen sector.

## 4 Conclusions

In summary, the relevance of a comprehensive and detailed approach to analyzing the low-carbon hydrogen production chain, with a focus on environmental, economic, social, and governance (EESG) dimensions, is highlighted. The systematic literature review and bibliometric analysis revealed significant trends, gaps, and essential scientific contributions. It was found that most research concentrates on the hydrogen production phase, while the stages of storage, distribution, and consumption receive less attention. This focus on production can be attributed to the urgent need to reduce carbon emissions and improve the economic viability of hydrogen technologies.

The results also indicate a predominant emphasis on environmental and economic dimensions, while social and governance dimensions are often underestimated. This imbalance suggests that, although environmental sustainability and economic viability are recognized as crucial, there is a significant gap in considering social impacts and the need for robust governance structures. In the long term, the success of the low-carbon hydrogen transition depends not only on technical efficiency and economic viability but also on social acceptance and the adequacy of regulatory policies. Therefore, a more balanced approach that integrates all ESG dimensions is essential to ensuring sustainable development.

This study makes a significant contribution to the field by providing a solid foundation for future research and policy formulation. The proposed recommendations aim to address the identified gaps by promoting greater integration of EESG dimensions. In particular, the need for increased attention to job creation, skills development, and the assurance of fair labor standards is emphasized, along with the strengthening of governance policies that can provide a stable and predictable environment for investments in the hydrogen sector. The analysis of keyword co-occurrences and the mapping of international collaborations underline the importance of global collaboration networks to accelerate technological and scientific advancements in the area.

The conclusions of the studies included in the PRISMA meta-analysis reinforce these observations. Most of the reviewed articles highlight the importance of emerging technologies and the need for specific policies to accelerate the transition to a green hydrogen economy. Despite the promising potential of green hydrogen, the studies point to significant barriers in terms of costs and technological development, which demand supportive policies throughout the entire innovation cycle, from research and development to the creation of competitive markets.

The studies also suggest that policies tailored to the specific needs of each sector and region may provide better results in terms of decarbonization and sustainability, rather than a one-size-fits-all

approach. This diversity of strategies is essential to effectively address the different industrial and regional realities.

Based on these findings, it is recommended that future studies explore more deeply the social and governance dimensions in low-carbon hydrogen production. The analysis of integrated approaches that holistically consider the economic, social, environmental, and governance impacts will be crucial to ensuring an energy transition that is not only effective in reducing emissions but also fair and inclusive. Additionally, it is vital that new research focuses on the application of hydrogen technologies in various industrial sectors and the exploration of best practices for developing policies that encourage the adoption and scalability of low-carbon hydrogen. These initiatives will contribute to the continuous advancement of the field and the realization of a more sustainable and resilient global economy.

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# Analysis of Low-Carbon Hydrogen Production in Landfills

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## Abstract

Urban solid waste management and the mitigation of greenhouse gas emissions are crucial global challenges for environmental sustainability. The production of low-carbon hydrogen, particularly in landfills, emerges as a promising alternative to address these issues. This study researches the potential and challenges of this technology, with a focus on the application of the Power-to-X concept in landfills, a topic of increasing relevance in the face of climate change and the search for more sustainable energy sources. Through a bibliometric analysis of scientific publications, a systematic literature review, and a prospective analysis of patent documents, this research explores the economic, environmental, social, and governmental aspects associated with this innovative approach. The results indicate significant growth in academic and technological interest in this area, highlighting the feasibility of converting biogas into hydrogen and the potential of this technology to contribute to decarbonization and the circular economy.

## 1 Introduction

The growing concern about climate change has driven the search for clean and renewable energy sources, promoting an energy transition towards a sustainable future. Various global conventions over the past decades have highlighted the need for a better balance between economic interests and nature preservation, especially given the increasing energy demand in production, transportation, and consumption processes, contrasted with the challenges of managing the resulting waste.

The United Nations Conference on Environment and Development, also known as the Earth Summit (Eco-92), and the Paris Agreement, adopted in 2015 during the 21st Conference of the Parties (COP 21) of the United Nations Framework Convention on Climate Change (UNFCCC), are important milestones in formulating public policies for sustainable development among signatory countries. The Paris Agreement, for example, aimed to combat global warming by setting targets to limit the global average temperature rise to well below 2°C above pre-industrial levels, with efforts to limit the increase to 1.5°C (IRENA, 2022).

Solid waste management is one of the greatest environmental challenges faced globally. With increasing population and urbanization, the amount of waste generated has exponentially grown, placing significant pressure on waste management systems. Landfills have recently been the predominant

solution for the final disposal of urban solid waste, providing a controlled and regulated way to store waste. However, the continuous use of these landfills raises crucial environmental and operational issues, such as the need to extend their lifespan and minimize associated environmental impacts (Brasil. Ministério do Meio Ambiente, 2022).

Although sanitary landfills represent an alternative to eliminating inappropriate disposal methods such as open dumps and controlled landfills, they face significant challenges related to management and environmental impact. Unlike sanitary landfills, controlled landfills are an intermediate solution where some environmental controls are applied, but they often lack the rigorous standards for waste treatment and containment. According to Brazil's National Solid Waste Policy (PNRS), over 50% of urban solid waste is organic, and its degradation in landfills is one of the main sources of methane emissions, making landfills the third-largest anthropogenic source of methane worldwide. This highlights the need for policies and practices that promote the reduction, recycling, and valorization of organic waste.

One such solution is the conversion of biogas generated by organic waste decomposition into hydrogen, which can be used directly as fuel or transformed into higher-value products such as synthetic methane or ammonia. The Power-to-X concept, involving the conversion of renewable electrical energy into hydrogen and its subsequent use in the production of synthetic fuels and chemicals, offers a promising approach (Orhan, M.F., & Dincer I., 2020). This enables the production of clean energy while fostering a circular economy by converting waste into valuable energy products.

Moreover, biogas recovery, mainly composed of methane, a potent greenhouse gas, can help reduce emissions and diversify the energy matrix by generating electricity, heat, or vehicle fuel (Fernandes et al., 2022).

This study aims to analyze the potential and challenges of low-carbon hydrogen production and the application of the Power-to-X concept in landfills, considering economic, technological, social, environmental, and governmental aspects.

## 2 Methodology

This study was conducted through a bibliometric analysis of scientific publications, a systematic literature review, and a prospective study of patent documents, with the aim of analyzing the technological, market, and scientific developments in the field of renewable energy. The searches were conducted in July and August 2024, using strategies focused on identifying a set of technologies related to low-carbon hydrogen, biogas, the use of urban waste in landfills, as well as the associated economic, social, environmental, and governmental aspects.

Initially, the Scopus database was used for data collection with two parameters to obtain more comprehensive results and allow for comparisons with patents throughout this article. In the first parameter, an advanced search was conducted using the following search strings: TITLE-ABS-KEY((hydrogen or h2) and (landfill or "urban waste" or wasteyard) and (biogas or "power-to\*")). For a more restricted analysis, only for comparison purposes, filters were applied for "Article" and "Review" in English, resulting in 289 articles.

In the second parameter, searches were conducted with the same strings but limited to articles published in the last 10 years (2014 - 2024) and written in English. The reading of the selected articles allowed for the application of the PRISMA method, where 191 articles and reviews were found, of which the 10 most cited were selected for detailed analysis. This selection enabled more effective data processing, organizing them into columns in an Excel spreadsheet, evaluating the presence of economic, environmental, social, and governmental factors in each scientific publication.

For the quantitative study, bibliometrics were used as a proven method to statistically analyze large amounts of information with scientific evidence (Boloy et al., 2021; Bortoluzzi et al., 2021; Rioset al., 2021). Additionally, searches were conducted in patent office databases, providing exclusive

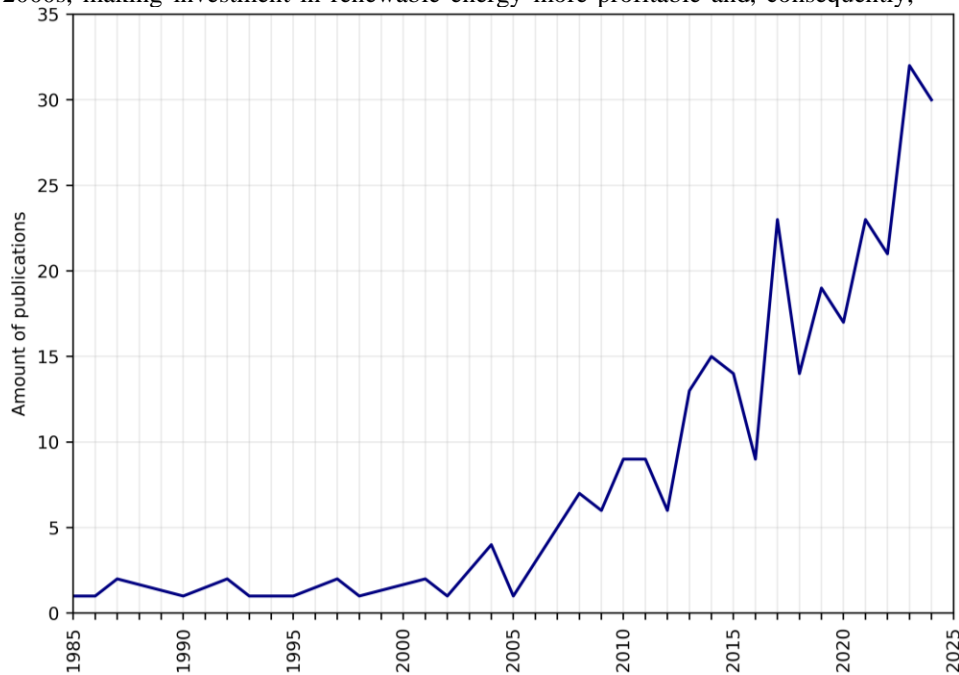
technological insights (Windels & Broek, 2017) and revealing scenarios for prospecting (Dehghanir et al., 2019; Sinigaglia et al., 2019; Spreafico et al., 2021).

In the analysis of patent documents (PD), Questel's Business Software Orbit Intelligence was used, which allowed for the investigation of technological trends over the years. This method is considered very efficient for investigating both the history and the state of the art in a technological area (Madani and Weber, 2016; Park et al., 2018) and has been used in important research on renewable energy (Abbas et al., 2014; Corrêa et al., 2024; Kim et al., 2018; Sampaio et al., 2018; Santos et al., 2022). The PDs were searched in the fields "title," "abstract," "claims," "description," and "object of invention," using the same string as for scientific publications, with no temporal restriction, in the FAMPAT database (Questel, 2021b), which is a global collection covering patent applications published by over 100 patent authorities (Questel, 2021a).

### 3 Results

#### 3.1 Bibliometric Analysis

In Figure 1, it can be observed that the number of documents published between 1985 and 2024 reveals a continuous growth pattern since 2006, with minor variations, and a strong increase in the last 7 years. This trend may have been influenced by several factors, including those impacting renewable energy as a whole, such as the pressure to reduce environmental impacts and the rise in oil prices in the early 2000s, making investment in renewable energy more profitable and, consequently,



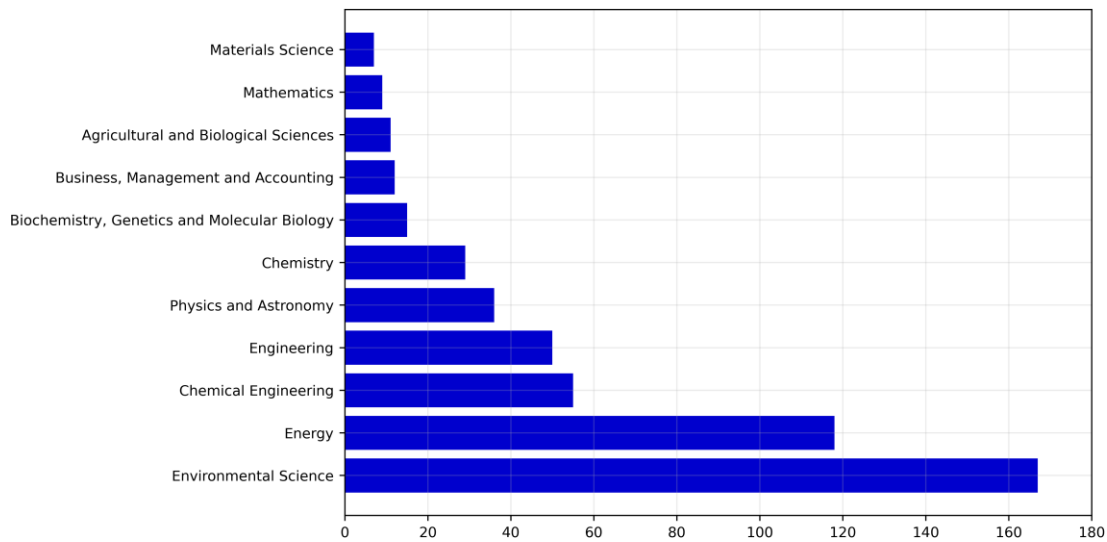
**Figure 1:** Evolution of publications over the years

increasing the amount of scientific research to provide the necessary foundation and knowledge for

technological and commercial advancements (Santos; Corrêa; Amaral; Gomes; Boloy, 2022).

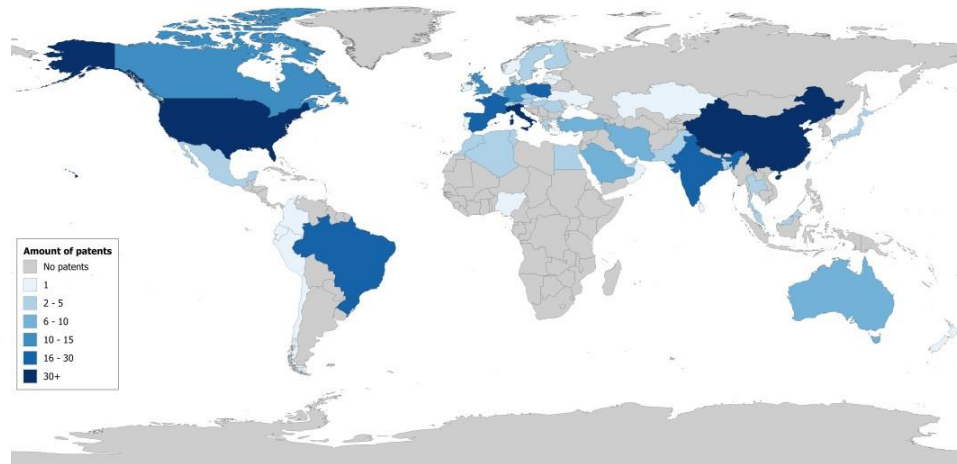
Regarding the thematic area (Figure 2), it was observed that most documents fall within the fields of environmental sciences and energy, indicating a strong interest in research related to energy efficiency, energy transition, and similar topics. Chemical engineering is also a significant area, likely related to the development of conversion processes and technologies for energy and materials.

This concentration of documents in environmental sciences and energy reflects the urgency and relevance of these topics in global contexts, such as climate change and energy transition. The areas of engineering, chemical engineering, and physics, although smaller in volume, are crucial as they provide the technological and theoretical foundations to advance these fields, demonstrating integration in clean and sustainable technologies.



**Figure 2:** Distribution of thematic areas

To identify the countries where these scientific research originate, Figure 3 shows the countries with the most publications, revealing China and the United States of America (USA) as global leaders in publications in this field.



**Figure 3:** Documents by country or territory

China is the country with the most publications. According to the International Renewable Energy Agency (IRENA, 2022), it plays a significant role in terms of incentives due to its carbon neutrality goals and ambitious policies and investments in renewable energy. China's national policies and strategies include hydrogen as a key component in its strategy, with long-term plans to achieve carbon neutrality by 2060.

The United States has also played a significant role by incorporating hydrogen into its energy and climate strategies. For example, the Hydrogen Utilization and Sustainability Act aims to expand tax credits for renewable electricity to include hydrogen and defines qualified hydrogen as having a carbon intensity of less than 75 gCO<sub>2</sub>/kWh (US Congress, 2021a).

Italy, according to IRENA (2022), is also making significant advances around low-carbon hydrogen. Italy has launched its National Hydrogen Strategy as part of its efforts to achieve carbon neutrality by 2050. The strategy includes developing hydrogen infrastructure and supporting research and innovation in hydrogen technologies, as well as investing in the construction of infrastructure to support hydrogen production, distribution, and use.

### 3.2 PRISMA Method

The data generated and analyzed in this section are the results of applying the PRISMA method. The scientific publications selected for this analysis cover a range of technologies and processes related to waste management and sustainable energy production. Ten publications were cited concerning economic factors, where these studies highlighted the potential for reducing operational costs and increasing profitability through the production of renewable hydrogen, demonstrating economic viability. Additionally, these studies suggest a greater economic visibility of clean energy technologies, indicating that investments in such technologies could result in significant long-term financial benefits.

Environmental factors were mentioned in all ten scientific publications. These studies highlight the importance of reducing greenhouse gas emissions and promoting more sustainable waste management practices, where the implementation of technologies for biogas and low-carbon hydrogen production significantly contributes to mitigating climate change and protecting the environment.

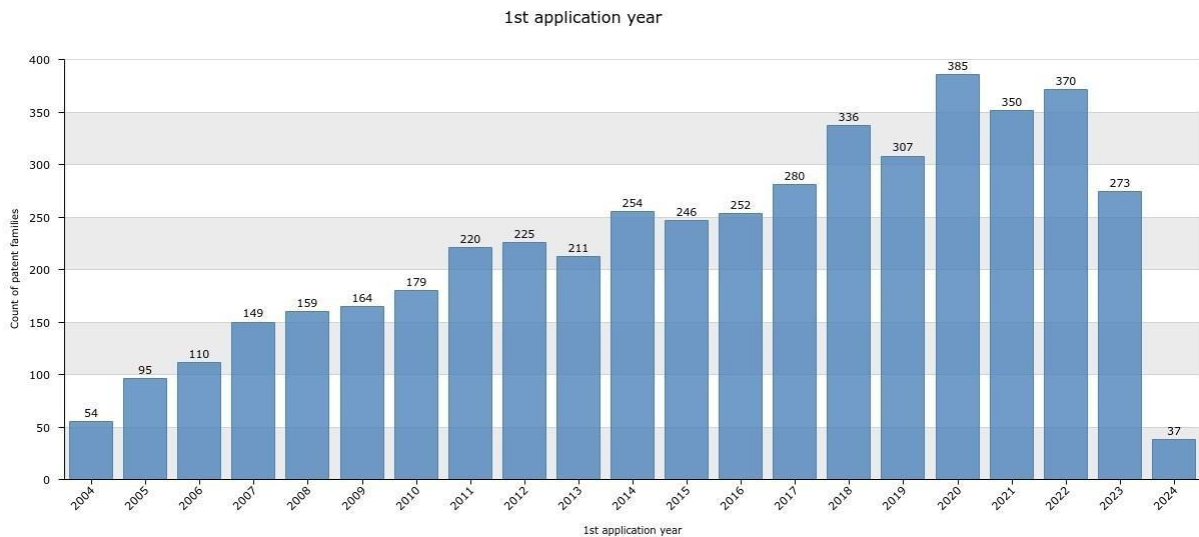
Only two publications addressed social factors, emphasizing the importance of public awareness and encouragement for more sustainable waste management practices. Education and societal awareness are crucial for adopting technologies and habits that promote sustainability and reduce

environmental impacts.

Regarding governmental factors, only three publications mentioned them. Although less frequently addressed, their role is extremely important due to government incentives and environmental policies that support sustainable technologies and practices. Creating favorable regulations and providing financial support are essential for the implementation and dissemination of clean energy technologies and more effective waste management practices.

### 3.3 Patent Analysis

A total of 5,213 patent documents were found (Figure 4). The results of the patent analysis indicate that, similar to scientific publications, there has been exponential growth since 2005. This can also be attributed to a series of significant global and national factors and milestones. Various public policies have been promoted to support research, development, and innovation for cleaner energy production, encouraging the decarbonization of the energy matrix. In addition to the previously mentioned global agenda for international agreements, many countries and regions have heavily invested in the development and commercial protection of their technological inventions. For example, the European Union's Hydrogen Strategy aimed to make hydrogen a central part of the European energy transition, impacting infrastructure investments for research and development, creating a hydrogen market, and encouraging the adoption of cleaner technologies across the region (IRENA, 2022).



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**Figure 4:** Number of patents per year

Figure 5 analyzes the patents, revealing a range of concepts related to the production of biogas in landfills and its application in the generation of low-carbon hydrogen and Power-to-X technologies. These concepts include biogas, methane, anaerobic digestion, electricity, contamination, reactors, among others with lesser prominence.

Through the highlighted key concepts, it was possible to identify connections indicating

technological routes in inventive activities. Biogas is produced through the anaerobic digestion of biomass in landfills and is fundamental as it converts organic waste into biogas composed of methane (CH<sub>4</sub>) and carbon dioxide (CO<sub>2</sub>). Methane, the primary component of biogas, can be used directly as a fuel or converted into hydrogen through processes such as steam reforming. Methane from biogas can be reformed to produce hydrogen, a process that can be conducted with low carbon emissions if the biogas originates from biomass waste.

Concepts

Anaerobic condition (563) | Anaerobic digestion (890) | Anaerobic fermentation (650) | **Biogas** (2205) | Biomass (788) | Carbon dioxide (667) | Carbon monoxide (675) | Co<sub>2</sub> (688) | Combustion (713) | Compressor (672) | Condensation (624) | Contaminant (653) | Contamination (1040) | Electricity (979) | Fermentation (593) | Heat exchanger (579) | Impurity (673) | Incineration (608) | Landfill (1075) | **Methane** (1325) | Methanediene (1179) | Microorganism (686) | Moisture content (559) | Natural gas (534) | Pipeline (615) | Pretreatment (583) | Reactor (712) | Recycling (581) | Sludge (565) | Wastewater (552) |

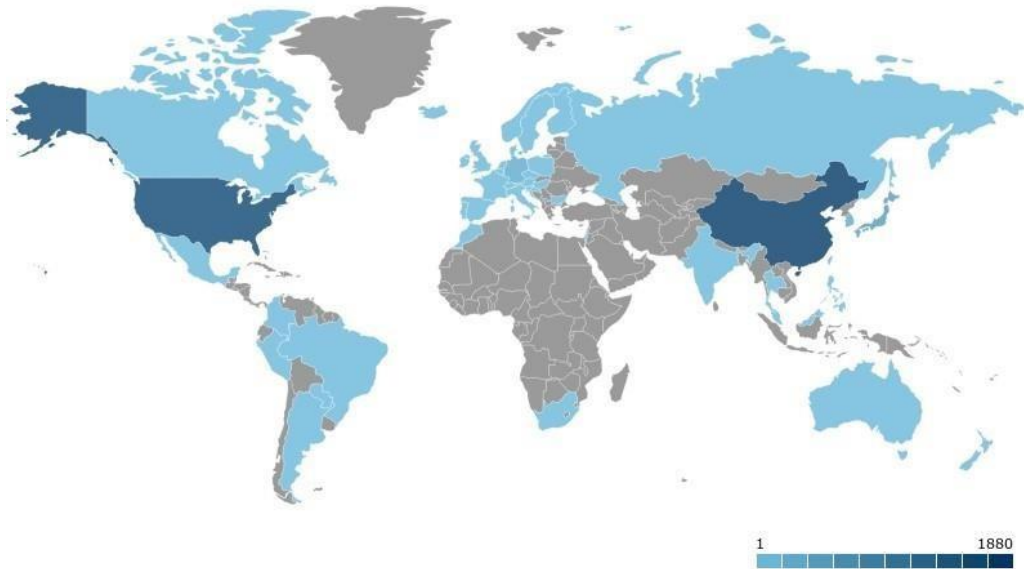
**Figure 5:** Relevant keywords

Between the words “Landfill” and “Contamination,” their connections are due to the importance of proper landfill management, aiming to maximize biogas capture while minimizing environmental contamination. The quality of this biogas can be significantly affected by contaminants, making adequate treatment necessary to remove impurities before using it for hydrogen production. Next, the word “Electricity” relates to this production because electricity generated from biogas is considered an efficient utilization method and can serve as a storage solution through the application of Power-to-X, allowing the sustainable use of the energy potential of organic waste.

Although the terms are less prominent, they are still important concepts in this topic. These include “Sludge,” “Wastewater,” “Pre-treatment,” “Compressor,” and “Pipeline.” “Sludge” and “Wastewater” are liquid and semi-solid waste that can be additional sources of biomass for biogas production. “Pre-treatment” refers to processes that can enhance anaerobic digestion efficiency, resulting in increased biogas production. “Compressor” and “Pipeline” are relevant for the transportation and storage of biogas and the hydrogen produced.

Figure 6 represents the origin of these technologies from the earliest patent filings in each office. Similar to scientific productions, new technologies are led by China with 1,880 patent filings and the USA with 1,656, demonstrating leadership in research, development, and innovation.

Priority country (without EP and WO)



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**Figure 6:** Patent distribution by country (without EPO and WIPO)

It is observed that, in addition to North America, two other regions stand out as developers and protectors of inventions related to technologies for hydrogen production from landfills: the Far East, where, besides China, Japan (488) and South Korea (260) are among the top 5; and the European Union, with notable patent filings at the European Patent Office (EPO) (299), Germany (245), the United Kingdom (124), and France (103). The large number of patent applications made at the World Intellectual Property Organization (WIPO) (1,504) indicates an intention to protect inventions in multiple countries, largely targeting the key countries. These results are consistent with the high levels of public and private investment in these regions.

## 4 Conclusions

This study highlighted the significance of low-carbon hydrogen production in landfills as an effective strategy for addressing contemporary environmental and energy challenges. The analysis showed that integrating the Power-to-X concept, using biogas from the decomposition of organic waste, offers integrated and sustainable solutions for waste management and clean energy production. Although barriers exist, they are surmountable with the implementation of appropriate public policies, technological investments, and social awareness. Prospects point to an increase in the adoption of these technologies, driven by the urgent need for energy transition and the search for more sustainable and resilient solutions. Thus, low-carbon hydrogen production in landfills not only promotes the reduction of greenhouse gas emissions but also represents a significant opportunity for energy matrix diversification and strengthening the circular economy. However, beyond the technical and economic

implications, it is crucial to emphasize the fundamental role of education in disseminating and adopting the technologies discussed in this study. Continuous commitment to scientific research and technological innovation is essential to leverage the country's potential and achieve a more sustainable and resilient future.

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# Synthesis of Nanostructured Perovskite for Intermediate-temperature Solid Oxide Fuel Cell

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## Abstract

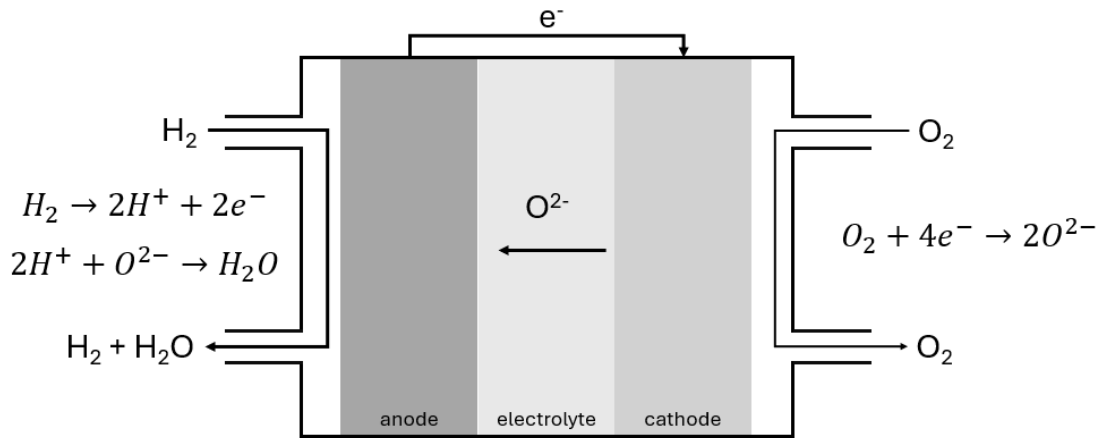
Solid oxide fuel cells are devices that directly convert chemical energy into electrical energy and consist of a cathode and an anode separated by an electrolyte. In this study, the Pechini sol-gel route was successfully used to prepare  $\text{La}_x\text{Sr}_{(x-1)}\text{Co}_y\text{Fe}_{(y-1)}\text{O}_3$  perovskites with properties suitable for the cathode construction of an intermediate-temperature solid oxide fuel cell (500 °C - 800 °C). This route allows the synthesis of perovskites with high porosity control, surface area, purity, and chemical homogeneity, improving their catalytic properties. Lanthanum, strontium, cobalt, and iron nitrates were used as precursors. Electron microscopy, X-ray diffractometry, and gas sorption were used to characterize the synthesized material. The obtained materials had an apparent intraparticle porosity suitable for gas transport through the ceramic structure, a high specific surface area for perovskite-type materials of  $16 \text{ m}^2 \cdot \text{g}^{-1}$  and a pore size of 4 nm, given by the presence of intraparticle mesopores and macropores formed by plate-like aggregates. The crystalline structure of the obtained samples is predominantly similar to a  $\text{La}_{0.6}\text{Sr}_{0.4}\text{Co}_{0.8}\text{Fe}_{0.2}\text{O}_{3-\delta}$  perovskite type.

## 1 Introduction

The phenomenon of global warming is currently associated with the continuous emission of greenhouse gases into the atmosphere due to the combustion of fossil fuels, which represent the world's primary energy source. This issue is further compounded by the rising demand for energy, which in turn increases the production and global consumption of these fuels (Rosa & Gomes, 2004). Significant resources have been allocated to mitigate these issues to develop alternative energy generation technologies, including hydro, micro-hydro, micro-turbines, biomass utilization, wind, photovoltaic cells, geothermal systems, and fuel cells. Fuel cells are efficient and silent electrochemical devices that directly convert the chemical energy of a fuel into electrical energy (Fernandes, et al., 2020). They are regarded as a promising technology for the generation of clean, renewable energy, due to their high efficiency in electricity generation (Vostakola & Horri, 2021). The most commonly utilized fuels are hydrogen, methane, hydrocarbons, methanol, and biogas. The utilization of pure hydrogen as fuel results in the emission of only water, thereby eliminating all other emissions (Kuterbekov, et al., 2022).

There are various types of fuel cells, but the greater flexibility of fuel use and their catalytic efficiency make solid oxide fuel cells (SOFC) the most advantageous among clean energy generation devices (Lama, 2006). Conversely, the operation of these cells necessitates the use of metallic and ceramic materials that exhibit high thermal and chemical stability, as well as ionic permeability, in their composition (Mahato, Banerjee, Gupta, Omar, & Balani, 2015). As an alternative, intermediate-temperature solid oxide fuel cells (IT-SOFC) with operating temperatures of approximately 500 °C to 800 °C have emerged (Mosiałek, et al., 2023).

A solid oxide fuel cell consists of at least a cathode and an anode separated by an electrolyte, all made of oxides, metal conductors, and sealants. The fuel (e.g., hydrogen or methane) is continuously supplied to the anode side, while an oxidizer (e.g., pure oxygen or air) is continuously supplied to the cathode (Singhal & Kendall, 2003). The fuel undergoes decomposition at the anode terminal. The electrolyte serves as an insulator for the electrons generated during the decomposition process, allowing only the positive ions (protons) to traverse from the anode to the cathode. The electrons released at the anode are conducted to the cathode via an external conductive circuit, where they are utilized for the reduction of oxygen. Consequently, an electric current is generated as a result of the flow of electrons within the external circuit. To increase the potential difference generated, fuel cells are often grouped in series (Mahato, Banerjee, Gupta, Omar, & Balani, 2015) (de Florio, Fonseca, Muccillo, & Muccillo, 2004). The conventional construction and operation of SOFC, which involve the cathodic reduction of oxygen ( $O_2 + 4e^- \rightarrow 2O^{2-}$ ) and the anodic oxidation of hydrogen ( $H_2 \rightarrow 2H^+ + 2e^-$ ), as well as the formation of water, are demonstrated in Figure 1.



**Figure 1:** Typical SOFC construction. Figure adapted from (Fernandes, et al., 2020)

The selection of an appropriate material is primarily contingent upon the ceramic material, the electrolyte, and the cell's operating temperature. It is essential to consider that this electrode is a porous structure, which must facilitate rapid mass transfer for both reactants and gaseous products. In cells that operate at lower temperatures, such as IT-SOFCs, the material selected for this electrode must possess specific properties to enable optimal performance. These include high electronic conductivity, chemical compatibility with the electrolyte, interconnectors, and sealants, stability in an oxidizing atmosphere, and high ionic conductivity (Nascimento & Mohallem, 2009).

Most undoped perovskite ( $ABO_3$ ) materials exhibit poor ionic conductivity. The partial replacement of the A-site cation (or the B-site cation) with receptor cations such as  $Sr^{2+}$ ,  $Ca^{2+}$ , and  $Ba^{2+}$ , or reducing  $Mn^{3+}$  ( $Co^{3+}$ ) to  $Mn^{2+}$  ( $Co^{2+}$ ) results in the formation of oxygen-deficient perovskites. These defects, i.e. this deficiency of oxygen sites (vacancy), enable ions to conduct in the perovskite structure. The conductivity values observed in some of these materials are comparable to those typically observed in solid electrolytes (Sun, Hui, & Roller, 2010). Moreover, the elevated temperatures within the cell and the octahedral symmetry surrounding the transition metal cations facilitate the formation of a semiconducting band structure, which in turn results in enhanced electronic conductivity (Sahini & Lupyana, 2023). Lanthanum (strontium-doped) and cobalt (iron-doped) perovskites (LSCF) have been studied due to their potential application as SOFC cathodes. This is attributed to their high ionic

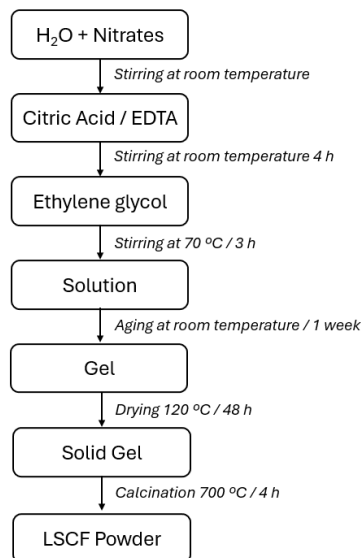
conductivity, high thermal and chemical stability, low difference in thermal expansion coefficient, and physical-chemical compatibility with other cell components (Felipe, et al., 2022)

A variety of techniques are employed in the synthesis of ceramic materials. In this study, the Pechini sol-gel method was successfully employed to synthesize LSCF perovskites using metal nitrates as precursors, citric acid ( $C_6H_8O_7$ ), ethylenediaminetetraacetic acid (EDTA) as chelating agents, and ethylene glycol ( $C_2H_6O_2$ ) as a polymerizing agent. The perovskite-type oxides obtained were found to possess the requisite properties for use as cathode materials in intermediate-temperature solid oxide fuel cells. In the selected synthesis route, the water content and synthesis parameters were adjusted to enhance the specific surface area. The principal benefit of this approach is the capacity to alter the structural configuration of the materials through the manipulation of synthesis parameters at a temperature approximating that of the ambient environment, which enables the controlled modification of properties pertinent to SOFC (Shivakumara, 2006).

## 2 Materials and Methods

The synthesis employs nitrates  $La(NO_3)_3 \cdot 6H_2O$  (99.5%, Neon),  $Sr(NO_3)_2$  (99%, Neon),  $Co(NO_3)_2 \cdot 6H_2O$  (98%, Dinâmica), and  $Fe(NO_3)_3 \cdot 9H_2O$  (99 %, Neon); citric acid  $C_6H_8O_7$  monohydrate (99.5%, Dinâmica); ethylenediaminetetraacetic acid (EDTA) (99%, ACROS), ethylene glycol ( $C_2H_6O_2$ ) (99.5%, Dinâmica) and distilled water.

The nanostructured lanthanum strontium cobalt ferrites (LSCF) were prepared using the Pechini method (Huizar-Félix, Hernández, Parra, Ibarra, & Kharisov, 2012). In the initial step the precursor solution was prepared by dissolving, at room temperature, the metal nitrates  $La(NO_3)_3$ ,  $Sr(NO_3)_2$ ,  $Co(NO_3)_2$ ,  $Fe(NO_3)_3$  with excess distilled water. The molar proportion was La: Sr: Co: Fe 6:4:8:2. Once the salts had been fully dissolved, citric acid was introduced, with a molar ratio 1:1 (metals nitrates: citric acid). In sample 2, EDTA was added to the solution. The mixture was stirred continuously for 4 hours. A certain quantity of ethylene glycol was added as the polymerizing agent. Subsequently, the mixture was heated in a water bath at 70 °C under continuous stirring for 3 hours. The sol obtained was subsequently aged for a week and heated in an oven at 120 °C for 48 hours to remove any residual solvents, thus forming a rigid resin. The resulting compound was calcined at 700 °C for four hours, removing all organic materials, to form LSCF agglomerates. The resulting material was disaggregated using a pestle and mortar for a few minutes. The summary of the synthesis used is shown in Figure 2.

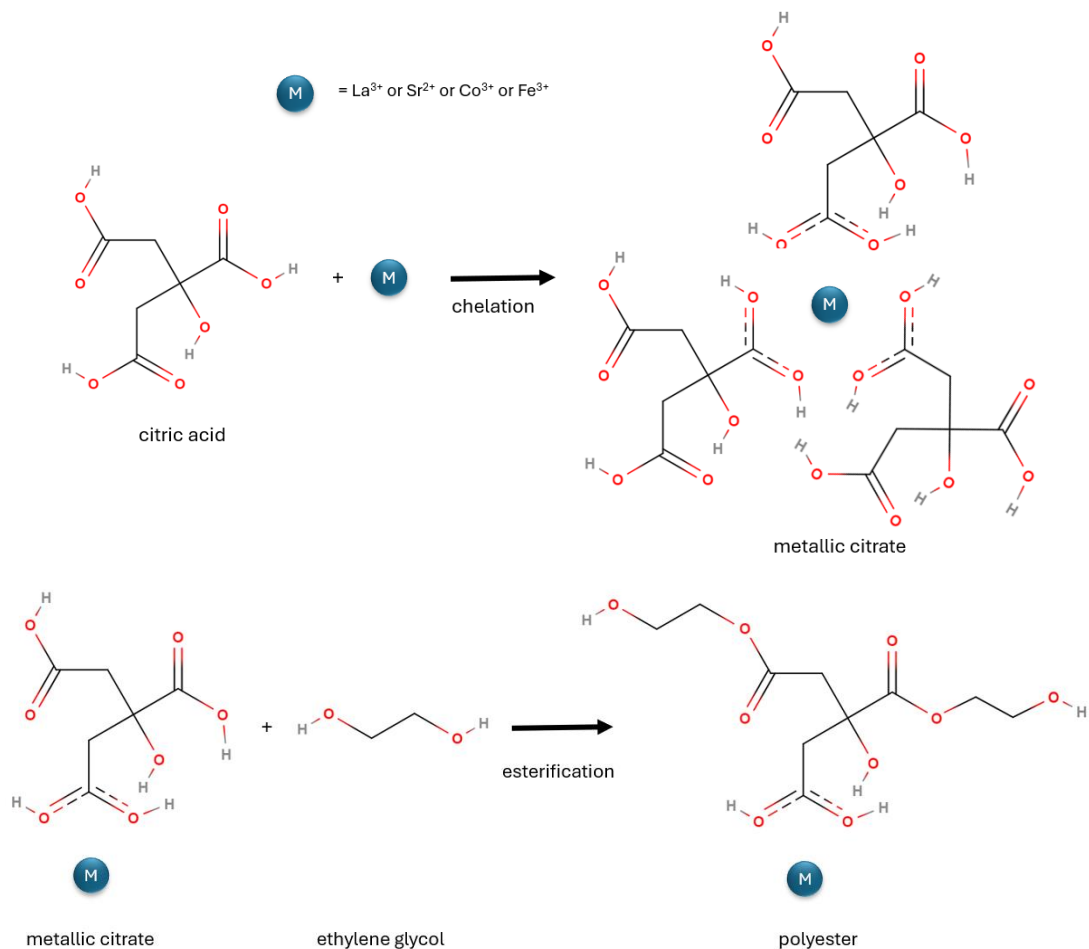


**Figure 2:** Schematic methodology used in this work.

The specific surface area and pore size distribution were measured using the gas sorption technique. The isotherms were obtained using Quantachrome equipment (model NOVA-2200e) at 77 K. Prior to analysis, the samples were degassed at 300 °C for three hours. The Brunauer-Emmett-Teller (BET) mathematical model was utilized to calculate the specific surface area, with the data collected within the relative pressure range of 0.05 to 0.35 undergoing analysis. To obtain the distribution and average pore size of the material, the density functional theory (DFT) models were utilized, which are particularly well-suited to the analysis of mesoporous materials (Landers, Gor, & Neimark, 2013). In this analysis, the nonlinear driving force (NLDF) equilibrium model for a cylindrical carbon pore at 77 K was considered. The samples were deposited on carbon tape and metalized with gold for three minutes with a current of 1.5 mA using the Sanyo Electron Quick Coater. The morphology was investigated using a Shimadzu SSX-550 scanning electron microscope with a secondary electron detector and a potential difference of 25 kV at varying magnifications. The phase composition of the obtained powder was characterized using X-ray diffractometry. The diffraction patterns were obtained using a Philips PANalytical diffractometer (model PW1710) with CuK $\alpha$  radiation ( $\lambda = 1.54$  nm) operated at 35 kV and 50 mA, with a continuous scan from  $2\theta = 10.0^\circ$  to  $2\theta = 89.9^\circ$  with a step of  $0.06^\circ$ . The diffractograms were subjected to qualitative analysis and comparison with the PDF2 database, and with the literature, with the objective of determining the crystal structure.

### 3 Results

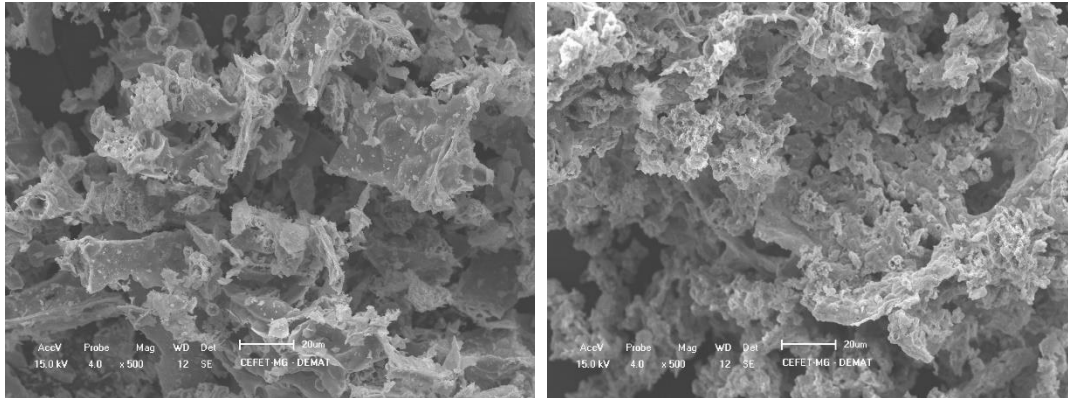
In the Pechini method applied to this experimental procedure, the two basic chemical reactions are the chelation (formation of complex ring-shaped compounds around the metal cations) between La<sup>3+</sup>, Sr<sup>2+</sup>, Co<sup>3+</sup>, and Fe<sup>3+</sup> with citric acid, and the subsequent polyesterification of hydroxycarboxylic acid with ethylene glycol. The resulting structures (metal-polyester) are cross-linked by continuing the esterification reaction at the remaining unreacted chain ends of the glycols that have bound to citric acid, to create a gel (Dimesso, 2018). These reactions are illustrated in Figure 3.



**Figure 3:** Schematic reactions of the Pechini method. Figure adapted from (Dimesso, 2018)

In this process, the metal cations are immobilized within the gel structure. Consequently, during the calcination stage, all organic species are pyrolyzed, resulting in the formation of metallic–oxygen bonds. This ultimately leaves nanoparticles or nanopores in the residual powder (Dimesso, 2018).

The final material obtained following the completion of the synthesis steps was observed to be a black, spongy solid. Figure 4 shows micrographs taken for the LSCF powder. The highly interparticle-porous structure of the solids is observed. The morphology observed is consistent with the random fragmentation of ceramic solids presenting irregular shapes and different sizes, a phenomenon commonly observed in monoliths produced by the sol-gel method (Gomes, et al., 2023). Nevertheless, the formation of a porous monolith is relevant to the intended application. A porosity of 20 % to 30 % has been reported as appropriate for the cathode on SOFC, enabling the supply of oxygen gas while maintaining high electrical conductivity (Niwa, Uematsu, & Hashimoto, 2013). The morphology of the sample that underwent synthesis with EDTA is illustrated in Figure 4b. This sample exhibited the formation of more compact solids. Conversely, the absence of EDTA, Figure 4a, led to the generation of slightly more spongy solids.

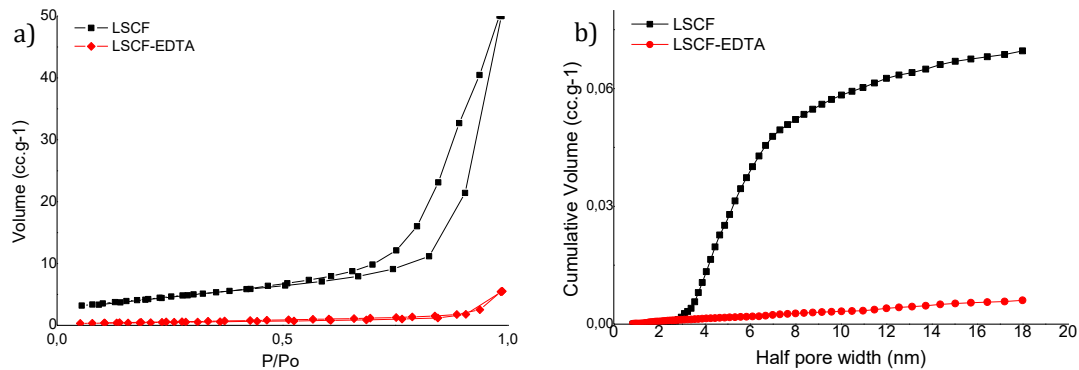


**Figure 4:** Scanning electron microscopy image of the samples: a) LSCF and b) LSCF\_EDTA.

The results of gas sorption obtained for LSCF powders prepared from the nitrates are shown in Table 1. The isotherms and the pore size distribution obtained are shown in Figure 5.

Sample	Specific surface area (m <sup>2</sup> .g <sup>-1</sup> )	Half pore width (nm)
LSCF	16 +/- 1	4,3 +/- 0,2
LSCF-EDTA	2 +/- 1	1,4 +/- 0,2

**Table 1:** Gas sorption results obtained of LSCF and LSCF-EDTA samples.

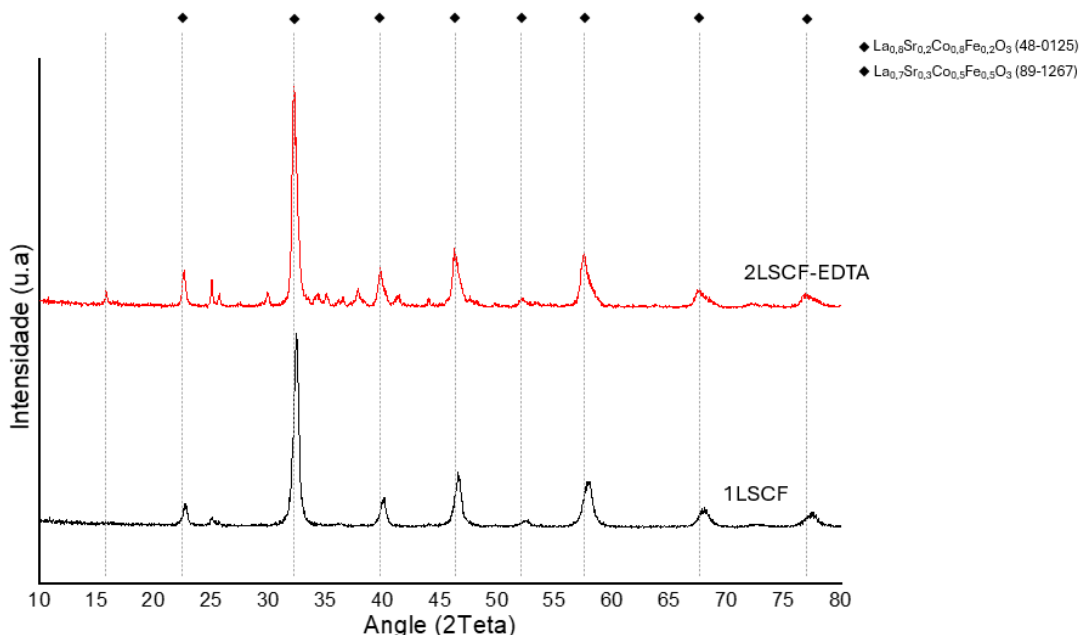


**Figure 5:** Gas sorption graphics obtained for LSCF and LSCF-EDTA: a) isotherms and b) pore size distribution.

Both samples exhibited a combination of Type III and Type IV isotherms, accompanied by H3 hysteresis. These results suggest the coexistence of intraparticle mesopores (2 nm to 50 nm) and macropores (> 50 nm) formed by plate-like aggregates (Thommes, et al., 2015). However, the adsorption volume on the surface of the LSCF sample was higher than that of the LSCF-EDTA sample, indicating that this sample possesses a larger surface area gas adsorption. An increased surface area is

a desirable behavior for catalytic applications. The conventional methods for the production of perovskite ceramic materials generate solids with a specific surface area below  $1 \text{ m}^2 \cdot \text{g}^{-1}$  (Gosavi & Biniwale, 2010). The LSCF sample, prepared without EDTA, exhibited a higher specific surface area ( $16 \text{ m}^2 \cdot \text{g}^{-1}$ ) and a higher average pore size (4,3 nm) than the sample LSCF-EDTA which presented  $2 \text{ m}^2 \cdot \text{g}^{-1}$  and 1,4 nm, respectively. A smaller pore size is expected to lead to a higher specific surface area. However, the specific surface area is also proportional to the quantity of pores. For perovskite materials produced by the Pechini method, a specific surface area of  $2 \text{ m}^2 \cdot \text{g}^{-1}$  to  $10 \text{ m}^2 \cdot \text{g}^{-1}$  is reported (Niwa, Uematsu, & Hashimoto, 2013; Yadav & Das, 2019). For coprecipitation methods, the reported range is from  $5 \text{ m}^2 \cdot \text{g}^{-1}$  to  $10 \text{ m}^2 \cdot \text{g}^{-1}$ . For non-aqueous sol-gel methods the reported range is from  $16 \text{ m}^2 \cdot \text{g}^{-1}$  to  $20 \text{ m}^2 \cdot \text{g}^{-1}$  (Gosavi & Biniwale, 2010; Huang, Sun, Zheng, Xiao, & Zhen, 2018). The results obtained for the LSCF and LSCF-EDTA samples suggest that this applied route has the potential to form a higher specific surface area perovskite material, compared to the most effective sol-gel method. The observed outcome for the LSCF sample, with a surface area of  $16 \text{ m}^2 \cdot \text{g}^{-1}$  is consistent and marginally higher than the reported results for a comparable approach (Zhang, et al., 2019) or one enhanced by EDTA (Fatah, Mohamad, Muchtar, & Hamid, 2021). Therefore, the incorporation of EDTA during the chelation process, as employed in this particular method, in this specific method, results in a denser sol and a reduction in the amount of solvent present within the network gel. Consequently, the application of EDTA results in a reduction in the porosity of the sample and its overall dimensions.

Figure 6 shows the diffractogram patterns of the samples. The detected XRD results indicate that the two samples were synthesized with a perovskite crystal structure, comparable to the  $\text{La}_{0.6}\text{Sr}_{0.4}\text{Co}_{0.8}\text{Fe}_{0.2}\text{O}_{3-\delta}$  standard cards (48-0125 and 89-1267) and comparable with publicized data (Chen, et al., 2020).



**Figure 6:** Diffractograms obtained for LSCF and LSCF-EDTA

The sample treated with EDTA exhibited the presence of additional crystalline phases, in minor proportions. These phases may represent isolated sites of lanthanum, strontium, cobalt, or iron oxides that were not organized in the desired  $\text{ABO}_3$  structure. The use of EDTA has been shown to alter the chelation process when compared to synthesis with citric acid, resulting in the formation of cross-linked

networks. However, the addition of EDTA causes the solution to have much higher acidity as compared to the use of citric acid (Fatah, Mohamad, Muchtar, & Hamid, 2021).

Perovskite-base materials have been employed as cathodes in solid oxide fuel cells. These oxides have the formula  $ABO_3$  where A and B are metallic cations with a total charge of +6. The “A” cations, which include La, Sr, Ca, and Pb, are larger and coordinated to 12 oxygen anions. While “B” cations, which include Ti, Cr, Ni, Fe, Co, and Zr, occupy a smaller space within the structure than “A” cations and are coordinated to six oxygen anions. Partial substitution of A and B cations for other cations with different valences introduces vacancies at the oxygen lattice sites (Sun, Hui, & Roller, 2010).

## 4 Conclusion

The sol-gel process, employing the Pechini method, was successfully utilized to synthesize nanoporous (nanostructured) perovskites of lanthanum, strontium, cobalt, and iron with a high specific surface area and good porosity within the mesoporous and macroporous range. However, the incorporation of EDTA as a co-adjuvant in the chelation process did not yield the desired outcome, namely the formation of nanoporous solids with a high surface area. This preliminary investigation demonstrates the potential of low-temperature chemical synthesis for the production of materials with a high specific surface area. In addition, the high chemical homogeneity attained during in the gel formation stages allows for the formation of oxides with controlled stoichiometry, thereby enhancing the efficiency of crystalline structure formation and consequently augmenting the catalytic activity of these compounds. The subsequent stages of this research will entail the assessment of alternative chemical synthesis routes, including the utilization of acetylacetonates instead of nitrates as a source of metallic cations and the investigation of the impact of incorporating modeling agents, such as block copolymers, before the gel formation stage.

## Acknowledgments

The authors would like to thank the Graduate Program in Materials Engineering of the Federal Center for Technological Education of Minas Gerais. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brazil (CAPES) - Finance Code 001.

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# Municipal Solid Waste Biorefineries: A Systematic Literature Review

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## Abstract

This article presents a systematic review of the literature on the global perspective of Municipal Solid Waste (MSW) biorefineries, conducted using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology. The analysis was based on documents retrieved from the Web of Science database, focusing on studies published in the last five years and written in English. The keywords used in the search were "municipal solid waste", "urban solid waste", "MSW" and "biorefinery." A total of 616 documents were initially identified. From this, 119 articles met the criteria established through PRISMA analysis. Of these, 10 were selected for meta-analysis, based on criteria such as citation frequency and recent publication date. These papers were then categorized into nine fields: author(s), title, publication year, research areas, energy conversion technologies, MSW fractions used for energy production, biofuels and bioproducts, and key findings. The main contribution of this paper is the identification of the potential for integrated technologies, where all fractions of the raw material can be effectively utilized and/or treated, leading to optimized energy recovery from waste and a reduction in the environmental impacts associated with its disposal. These findings highlight the role of integrated MSW biorefineries in the energy transition and decarbonization efforts.

Keywords: Municipal Solid Waste, biorefinery, Systematic Review, PRISMA

## 1 Introduction

Currently, the global scenario demonstrates a close relationship between the quantity and quality of energy available and the advancement of the economy, resulting in increasingly intense conflicts between industrial development, environmental deterioration and the scarcity of resources. The rapid and exponential growth of the population, which is expected to reach 50 million people by 2050, poses challenges not only for the supply of energy and materials, but also for the management of municipal solid waste (MSW) [1-3].

MSW is a residual resource that requires immediate attention and effective management techniques. Two of the United Nations Sustainable Development Goals (SDGs), Goal 12 (Responsible Consumption and Production) and Goal 11 (Sustainable Cities and Communities) address this issue. Furthermore, an additional goal (Goal 7: Clean and Affordable Energy) can also be achieved if MSW is converted into biomass for bioenergy generation [4].

In this scenario, the concept of municipal solid waste biorefineries is emerging as an innovative and sustainable approach to the management and recovery of MSW. Inspired by the biomass biorefinery model, this concept proposes the integral conversion of waste into high value-added products such as biofuels, biochemicals, bioenergy and other bioproducts. The central idea is to maximize the use of all waste fractions, minimizing waste and promoting the circular economy [3].

MSW biorefineries stand out for their ability to integrate various conversion technologies, such as anaerobic digestion, pyrolysis, gasification and fermentation, allowing different components of waste to be transformed into useful products. For example, the organic fraction of MSW can be converted into biogas or biofertilizers, while plastics and other inorganic materials can be processed to produce liquid fuels or synthetic gases. This integrated approach not only optimizes the recovery of energy and materials, but also significantly reduces the volume of waste destined for landfills, helping to reduce environmental impacts [3][5].

In addition to the environmental benefits, MSW biorefineries play an important role in promoting economic and social sustainability, converting waste into resources, it creates new job opportunities, foster technological innovation and reduce dependence on fossil fuels [1]. These facilities can be key to the energy transition, offering an alternative source of renewable energy and helping to reduce carbon emissions. Furthermore, the implementation of biorefineries can improve waste management in cities, making them more resilient and adapted to the challenges of the future [3].

However, the implementation of MSW biorefineries faces technical, economic and regulatory challenges that need to be overcome if their potential is to be fully realized. The complexity of waste composition, the need for robust and integrated technologies, and the costs involved in building and operating these plants are all issues that require attention. In addition, effective public policies and economic incentives are essential to enable and stimulate the development of this sector [1-3][5].

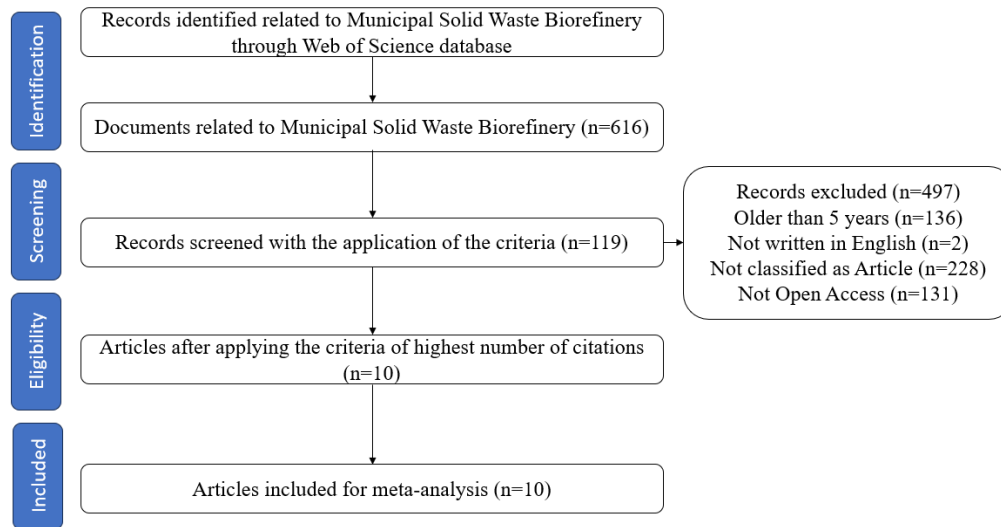
This paper proposes a detailed analysis of municipal solid waste biorefineries; by reviewing the existing literature and evaluating practices in different regions of the world, it seeks to identify the main challenges and opportunities associated with this innovative approach to waste management. It is hoped that this study will contribute to the advancement of knowledge on the subject and to the promotion of more sustainable and integrated solutions in MSW management, in a context of growing demand for more responsible and efficient environmental practices.

## 2 Materials and Methods

To conduct a comprehensive analysis of Municipal Solid Waste Biorefinery, a systematic literature review was performed using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) method, which is widely recognized for ensuring rigor and transparency in systematic reviews [6-8]. The review was guided by a specific research question, which directed the definition of inclusion and exclusion criteria as well as the search and selection process of the studies.

The search strategy was developed with the assistance of Web of Science database in July 2024. The keywords used were "Municipal Solid Waste," "Urban Solid Waste" "MSW", "Biorefinery", "Waste Biorefinery" and "Zero-Waste Biorefinery" combined using the Boolean operators "AND" and "OR" to refine the results. The search was limited based on rigorous criteria: studies published in the last five years and written in English, thereby ensuring the relevance, classified as articles and published in Open Access. After this, the data was treated through the OpenRefine software, an tool for cleaning matter, messy data, duplicate removal, and transforming formats.

The selection process involved three main stages: initial screening of titles and abstracts and detailed evaluation of full-text articles. For the purpose of the study, the ten most cited articles among the given criteria were selected for the meta-analysis. The number of studies identified, included, and excluded was documented using the PRISMA flow diagram (Figure 1) [6-8].



**Figure 6:** Detailed flowchart illustrating the PRISMA meta-analysis steps.

After selection, data from the included studies were extracted using a standardized form, capturing information such as study details, context, methodology, key findings, and conclusions. In addition, information such as the fraction of MSW valued, the conversion technology and the integration between technologies, as well as the bioproduct and/or biofuel produced in each study were also highlighted.

These data were then qualitatively synthesized, organized into relevant thematic categories, and compared to identify patterns, gaps in the literature, and opportunities for future research. The results were presented in a narrative format, supplemented by tables and graphs summarizing the main information and trends identified. When possible, a meta-analysis was conducted to quantify the combined effects of the included studies [6-8].

### 3 Results and Discussion

The results of the PRISMA meta-analysis are showing in detail the Table 1 developed with the main information of the articles selected based on pre-established criteria.

Ref.	Title	Year	Keywords	Purpose	Key findings
[9]	Bioenergy and bio-products from bio-waste and its associated modern circular economy: Current research trends, challenges, and future outlooks	2022	Explore the potential of generating bioenergy and bioproducts from biowaste; Modern circular economy; Biowaste; Bioproducts and bioenergy; Sustainable models; Challenges; Lignocellulose.	Analyze the current state and potential of biowaste utilization;	It emphasizes the need for advanced biorefinery technologies and innovative bioproducts to maximize the value of biowaste; highlight the critical role of policy support and technological advancements in overcoming the challenges associated with biowaste management and in realizing the full potential of a circular bioeconomy.
[10]	Environmental life cycle assessment of different biorefinery platforms valorizing municipal solid waste to bioenergy, microbial protein, lactic and succinic acid	2020	Circular bioeconomy; Biorefinery; Single cell protein; Lactic acid; Succinic acid; Municipal solid waste	Explore urban biowaste biorefinery scenarios;	All developed platforms were found as eco-friendly solutions for waste valorization. Scenarios focusing on bioenergy outperformed others from environmental viewpoint.
[11]	An urban biorefinery for food waste and biological sludge conversion into polyhydroxyalkanoates and biogas	2020	Organic fraction of municipal solid waste (OFMSW); Waste activated sludge (WAS); Polyhydroxyalkanoates (PHA); Anaerobic co-digestion (ACoD); Volatile fatty acids (VFA)	Urban biorefinery technology chain has been developed at pilot scale in the territorial context of the Treviso municipality (northeast Italy) for the production of biopolymers (polyhydroxyalkanoates, PHAs) and biogas from waste of urban origin.	The platform gives interesting and useful data, especially related to the overall PHA yield and preliminary economic evaluations; each urban scenario needs to be specifically evaluated in terms of production and composition of organic waste;
[12]	Integration of Hydrothermal Carbonization with Anaerobic Digestion; Opportunities for Valorization of Digestate	2019	hydrothermal carbonization (HTC); anaerobic digestion (AD); waste management; biorefinery; digestate; pyrolysis; hydrochar; slagging and fouling; biogas; biodegradability	This study compares the Hydrothermal carbonization of digestates from anaerobic digestion (AD);	The integration of HTC is beneficial to treat digestate and enhance biogas yields via anaerobic digestion of process waters. Hydrochar produced is not recommended as a solid fuel;

[13]	Optimization of urban waste fermentation for volatile fatty acids production	2019	Organic fraction of municipal solid waste (OFMSW); Volatile Fatty Acid (VFA); Waste Activated Sludge (WAS); Biorefinery; Anaerobic fermentation	This paper deals with the optimization of the fermentation process in order to transform urban organic waste into added-value volatile fatty acid (VFA) rich stream, useful for biological processes within a biorefinery technology chain.	An optimized fermentation process is crucial in a biorefinery perspective since it has to give a final stream of constant composition or tailored products suitable for further applications.
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**Table 1:** Main characteristics and results of the ten articles selected, PRISMA Analysis (Continued).

Ref.	Title	Year	Keywords	Purpose	Key findings
[14]	Food wastes and sewage sludge as feedstock for an urban biorefinery producing biofuels and added-value bioproducts	2020	biorefinery; anaerobic digestion; volatile fatty acids; biogas; house hold food wastes; polyhydroxyalkanoate; digestate; sewage sludge;	biorefinery platform in which food waste and sewage sludge are adopted to produce volatile fatty acids (VFAs) through a dark fermentation process.	A more innovative use of biogas is emerging in its adoption for PHB production; The biorefinery loop is closed by nitrogen and phosphorus recovery from digestate; Bio-based products and biofuels come from, they need to be accepted by the market;
[15]	Organic waste biorefineries: Looking towards implementation	2020	Organic waste; Biorefinery; Pre-treatment; Biological processes; Thermal processes; Implementation;	The drivers that can make the MSW biorefinery concept applicable to waste management and the possibilities for its development to full scale.	The heterogeneity of waste implies additional complexity in biorefineries. Technological, strategic and market constraints affect implementation. Interventions from policy makers are necessary to foster sustainable bio-based solutions for waste management.
[16]	Sustainable management of municipal solid waste through waste-to-energy technologies	2022	Waste to energy; Circular bioeconomy; Sustainability; Bioenergy; Biorefinery;	Provide a comprehensive overview of the existing scenario for sustainable MSW management along with the bottlenecks and perspectives;	The most feasible MSW management solutions in developing countries include anaerobic digestion for organic wastes, incineration for mixed MSW (other than bio-waste), pyrolysis, and gasification for

					specific wastes (electronic devices, woody biomass, etc.);
[17]	Sequential bioethanol and methane production from municipal solid waste: An integrated biorefinery strategy towards cost-effectiveness	2021	Anaerobic digestion; Bioethanol; Fermentation; Methane; Organic fraction of municipal waste;	The organic fraction of municipal waste (OFMW) was used as raw material for the sequential production of bioethanol and biogas.	Overall, bioconversion of OFMW would benefit from coupling bioethanol and biogas production since the biogas produced might be further employed as bioenergy source to compensate operational costs.
[18]	Biofuel production by hydro-thermal liquefaction of municipal solid waste: Process characterization and optimization	2023	Hydrothermal liquefaction; Municipal solid waste; Bio-crude oil; Optimization;	In this investigation, the HTL method was employed to produce biofuel from municipal solid waste (MSW).	Based on the results, biofuel production has an upward trend by increasing temperature to 364.57 degrees C and reaction time to 88.23 min. Whereas, there is an inverse relationship between the biofuel waste-to-water ratio, in both the context of mass and energy yield.

**Table 1:** Main characteristics and results of the ten articles selected, PRISMA Analysis.

The studies summarized in Table 1 are multiple disciplines (N = 10), comprising experimental research articles (N = 5), reviews (N = 2), and feasibility studies (N = 3), where include Life Cycle Assessment (LCA) analyses, techno-economic evaluations, and Mass and Energy balances in in the methodology. The research has been conducted across various countries and regions: China (N = 3), Italy (N = 3), England (N = 2), Spain (N = 1), and India (N = 1). Notably, countries from the American continent, such as the USA and Brazil, are absent from the list of authors of the most impactful articles on this topic. However, these countries do feature prominently among the leading nations publishing on the subject when analyzing the last five years of articles that meet the PRISMA criteria, prior to selecting the most cited works.

A plausible explanation for the dominance of European and Asian countries in this research area is the presence of more stringent regulations on municipal waste disposal in Europe, which heightens the urgency for waste recovery initiatives. Additionally, countries like China and India, with their large populations, face more pronounced challenges related to municipal solid waste management. Moreover, these nations are under significant pressure to transition to cleaner energy matrices and reduce greenhouse gas emissions.

When evaluating the alignment of these studies with the Sustainable Development Goals (SDGs), three specific goals are prominently addressed:

- SDG 7: Affordable and Clean Energy (N = 2);
- SDG 11: Sustainable Cities and Communities (N = 1);
- SDG 12: Responsible Consumption and Production (N = 8).

Among these, SDG 12: Responsible Consumption and Production is the most frequently addressed, whereas SDG 7: Affordable and Clean Energy is just mentioned in [12] and [18]. This indicates that Municipal Solid Waste (MSW) is still not widely recognized as a resource for bioenergy production. Instead, the MSW biorefinery model is primarily implemented to fulfill target 12.4 of SDG 12, which aims to achieve environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with international frameworks, and significantly reduce their release into the air, water, and soil to minimize adverse impacts on human health and the environment [4].

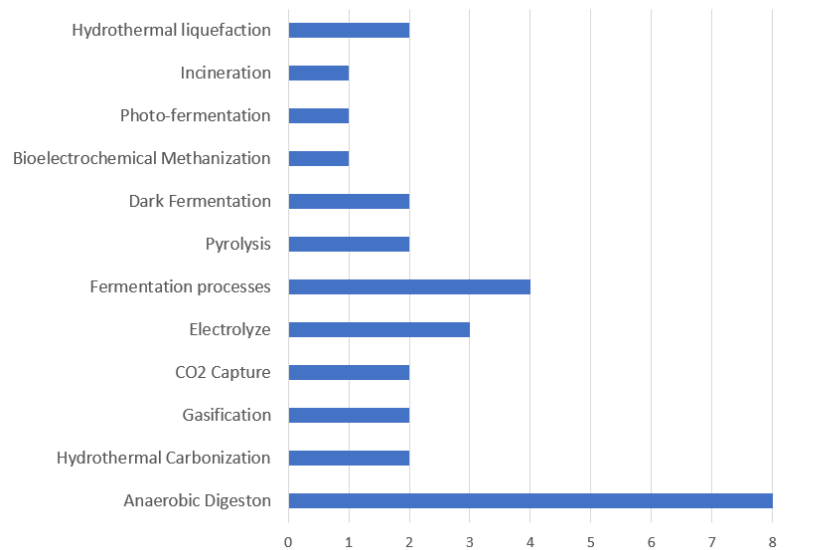
In the Table 2, is it possible to analyze the Research Areas to through PRISMA method.

<b>Research Areas</b>	<b>N° of documents</b>
Energy & Fuels	4
Engineering	6
Science & Technology	1
Environmental Sciences & Ecology	4
Water Resources	1
Chemistry	1
Agriculture; Biotechnology & Applied Microbiology	1
Biotechnology & Applied Microbiology	1

**Table 2:** Research areas analyzed through PRISMA method.

Most of the articles studied pointed to more than one area of research. As can be seen, the area that appear the most was “Engineering”, which present 6 documents, follow by “Energy & Fuels” and “Environmental Science & Ecology”, which 4 documents each one. The authors [9][10][12][17] are focusing to try to apply the waste conversion to generate energy and to mitigate the negative impacts caused to the environment, when inappropriately disposed. All the others research areas appear just once.

The proposed configurations for Municipal Solid Waste (MSW) biorefineries were also analyzed. A review of the studies reveals that most approaches focus primarily on the Organic Fraction of Municipal Solid Waste (OFMSW), with only two studies [16][18] considering MSW in its entirety. The primary challenge highlighted by most authors is the heterogeneity and complexity of MSW components, which complicates the selection of suitable conversion technologies and their potential integrations [9-18]. To address this, several configurations propose combining organic waste with other materials such as sewage sludge [12][14][15], and lignocellulosic biomass [9]. This blending is likely aimed at improving waste homogeneity, thereby enhancing process efficiency and reducing contamination risks, particularly from components like heavy metals.



**Figure 2:** Chart of conversion technologies identified in the MSW biorefinery configurations proposed in the articles analyzed using the PRISMA Method.

Figure 2 illustrates the conversion and valorization technologies identified in the studies, along with their frequency of occurrence in various configurations. Anaerobic Digestion (AD) emerges as the most common and traditional process, featured in nine out of the ten MSW biorefinery configurations evaluated. AD is frequently coupled with biogas upgrading and purification processes, such as CO<sub>2</sub> capture techniques [10][16]. Several studies also propose various pre-treatment methods for OFMSW to optimize the AD process. For the digestate resulting from AD, multiple authors suggest its application as a biofertilizer, using composting processes. Additionally, Nitrogen and Phosphorus recovery processes are proposed for similar purposes [14]. One study even recommends Hydrothermal Carbonization of the digestate to produce biochar, which can be used as a soil adsorbent [12].

Fermentation processes are another recurring theme in several MSW biorefinery configurations. The studies identify various methods, including acidogenic fermentation, non-isothermal and simultaneous saccharification and fermentation (NSSF), alcoholic fermentation for bioethanol, Volatile Fatty Acids (VFAs) and biopolymers producing. Emerging technologies such as dark fermentation and photo-fermentation are also mentioned. These methods are often associated with AD processes to produce hydrogen (H<sub>2</sub>) [14-15].

Electrolysis appears in three studies as an alternative method for H<sub>2</sub> production, particularly in configurations that incorporate wastewater recovery. Technologies such as gasification, pyrolysis, and hydrothermal liquefaction are also included in biorefinery designs that process various fractions of

MSW, not limited to the organic fraction [16].

Table 4 illustrates the distribution of the 10 different biofuels and value-added bioproducts produced within the MSW biorefinery configurations analyzed. The data reveals a significant emphasis on gaseous biofuels, with biogas (N=9), biomethane (N=4), syngas (N=2), and hydrogen (N=6) being the most commonly produced outputs. Among these, biogas emerges as the most frequently produced, largely due to its role as a primary product of anaerobic digestion processes. However, biogas is often not the final product within these biorefineries. Instead, it serves as a precursor to higher-value biofuels such as hydrogen and biomethane, which are obtained through subsequent upgrading and optimization processes [9-10][16-17]. These optimized biofuels are of greater economic value in current energy markets due to their higher energy content, purity, and applicability in various sectors.

<b>Biofuels or bioproducts</b>	<b>N° of documents</b>
Biomethane	4
Hydrogen	6
Biogas	9
Syngas	2
Composting/biofertilizer	4
Volatile Fatty Acid (VFA)	4
Biopolymers	4
Biochar	1
Bioethanol	3
Bio-oil	2

**Table 4:** Biofuels and value-added bioproducts produced through MSW valorization in biorefinery configuration.

Hydrogen, in particular, is increasingly valued for its role in the transition to a low-carbon economy, as it can be used as a clean fuel in fuel cells or as a feedstock in various industrial processes [9]. Similarly, biomethane, which is essentially purified biogas, can be directly injected into existing natural gas networks, making it a versatile and valuable product [9]. Additionally, syngas, a mixture of carbon monoxide and hydrogen, is produced through gasification processes and serves as a versatile intermediate that can be converted into various chemicals, fuels, and energy [9][16].

Bioethanol production is noted in three of the studies and represents an important liquid biofuel option. As a readily marketable fuel, bioethanol holds significant commercial value and offers a relatively straightforward pathway for adding value to the MSW biorefinery product chain. It can be blended with gasoline to reduce carbon emissions from transportation or used in the production of bio-based chemicals [16-17].

When it comes to value-added bioproducts, biofertilizers are the most frequently mentioned. These products result from the stabilization and nutrient recovery processes of anaerobic digestate, offering a sustainable alternative to synthetic fertilizers. However, commercialization of biofertilizers presents challenges, primarily due to the heterogeneous nature of the input waste, which can lead to variability in the nutrient composition and quality of the final product [10]. To overcome these challenges, [14] suggest focusing on the recovery of specific nutrients, such as phosphorus and nitrogen, from the digestate. These recovered nutrients can then be sold as concentrated soil amendments, providing a more consistent and marketable product.

Biochar is another bioproduct identified in the [12], produced through the thermal processing of digestate via pyrolysis or hydrothermal carbonization. Biochar is valued for its potential to improve soil health by enhancing water retention, reducing nutrient leaching, and sequestering carbon. However, like biofertilizers, biochar faces commercialization difficulties due to inconsistent quality and market acceptance.

Finally, the production of biopolymers, such as polyhydroxyalkanoates (PHAs), represents an emerging area within MSW biorefineries [14-16]. These biodegradable plastics can be produced from various organic waste streams and are positioned as sustainable alternatives to conventional, petroleum-based plastics. The use of biopolymers in sectors such as packaging not only adds value to the MSW biorefinery chain but also contributes to the reduction of plastic waste, aligning with global sustainability goals.

## 4 Conclusion

The comprehensive review of Municipal Solid Waste (MSW) biorefineries highlights their significant potential to contribute to sustainable waste management and the production of renewable energy and valuable bioproducts. The analysis of various biorefinery configurations reveals that although the organic fraction of MSW is the primary focus, there is a growing interest in developing technologies that can effectively process heterogeneous waste streams.

Anaerobic digestion (AD) remains the cornerstone technology in most biorefinery setups, primarily due to its established reliability and efficiency in converting organic waste into biogas. However, the review underscores the importance of optimizing biogas through upgrading processes to produce higher-value fuels such as biomethane and hydrogen, which are increasingly recognized for their roles in the clean energy transition. The production of biofuels and bioproducts such as bioethanol, biofertilizers, and biopolymers further demonstrates the versatility of MSW biorefineries.

However, challenges remain, particularly in the commercialization of bioproducts, which is hindered by the heterogeneity of the waste input and the resulting variability in product quality. To address these challenges, further research and development are needed to standardize processes and improve the marketability of MSW-derived products. Additionally, policy support and economic incentives will be crucial in driving the adoption of MSW biorefineries at a larger scale.

In conclusion, MSW biorefineries represent a promising and necessary innovation in the pursuit of circular economy principles and sustainable urban development. By converting waste into valuable resources, these systems not only reduce the environmental burden of landfills but also contribute to energy security and greenhouse gas mitigation. Future research should focus on the integration of advanced technologies and the development of holistic approaches that consider the full life cycle of waste, ensuring that MSW biorefineries can be implemented effectively and sustainably across diverse geographic and socioeconomic contexts.

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# Eco-Efficiency and Economic Assessment of Electric Vehicle Technologies

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## Abstract

This study employs three distinct methodologies to assess the eco-efficiency of electric vehicles (EVs): analysis of endpoint damage categories for major components, evaluation of whole-vehicle endpoint damage categories, and Life Cycle Cost (LCC) analysis as an economic indicator. Each method offers unique insights into the environmental and economic performance of EVs. The findings highlight significant variations in eco-efficiency among different EV types. Hybrid Electric Vehicles (HEVs) and Plug-in Hybrid Electric Vehicles (PHEVs) consistently outperform conventional models, with eco-efficiencies up to 31.34% and 74% higher, respectively, than the conventional comparison model. This research underscores the critical importance of integrating both direct costs and environmental impacts when assessing the sustainability of EVs. Such insights are important for informing strategic decisions aimed at advancing sustainable automotive technologies and policies.

## 1 Introduction

Eco-efficiency, which integrates environmental and economic performance metrics, is increasingly significant in evaluating electric vehicles. As nations strive to reduce overall environmental impacts and combat climate change, understanding the eco-efficiency of various vehicle technologies becomes crucial. Electric vehicles, including hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and fuel cell hybrid electric vehicles (FCHEVs), offer promising alternatives to traditional internal combustion engines. However, concerns persist about their environmental impacts throughout their lifecycle, including production, operation, and end-of-life stages.

Recent research has shed light on different aspects of eco-efficiency within the electric vehicle sector. (Koh et al., 2021) examined a hybrid energy storage system combining first-life and second-life battery technologies, including lithium titanate and electric vehicle batteries. The research utilised life cycle assessment (LCA) and techno-economic analysis to evaluate eco-efficiency from cradle-to-grave. The study revealed that a hybrid system with a balanced proportion of first and second-life batteries achieved optimal eco-efficiency, demonstrating how battery life cycle considerations can minimise environmental and economic impacts.

Kutty et al. (2021) assessed electric vehicle efficiency across 28 EU member states by analysing water consumption, greenhouse gas emissions, energy consumption, and gross domestic product contribution. The study employed data envelopment analysis and clustering techniques to categorise countries into high, medium, and low-efficiency groups. It concluded that countries using solar energy demonstrated superior efficiency compared to those relying on mixed-source energy.

Onat et al. (2021) investigated the eco-efficiency of electric vehicles in Europe through LCA and principal component analysis. The study considered various environmental indicators, such as carbon footprint and water consumption, along with an economic indicator (GDP contribution). The results identified Belgium, Spain, Denmark, and Germany as the most eco-efficient countries, while Estonia and Bulgaria were found to be less eco-efficient. The study suggested that low-efficiency countries could benefit from adopting practices of higher-efficiency nations.

Onat et al. (2019) employed principal component analysis and LCA to develop an integrated framework for assessing battery electric vehicles in the USA. The study explored three electricity production scenarios: marginal electricity mix, average electricity mix, and 100% solar energy. It found that states using a 100% solar energy scenario achieved the highest eco-efficiency, highlighting the significant environmental benefits of solar-powered electric vehicles.

Onishi et al. (2020) evaluated the eco-efficiency of renewable-driven microgrid systems, including plug-in electric vehicles, using a model that integrated photovoltaic, wind, and hydrogen energy sources. The study found that optimal operation of vehicle-to-grid technologies and time-of-use pricing could reduce energy and environmental costs by approximately 42%, underscoring the benefits of integrating renewable energy sources and smart grid technologies.




Philippot et al. (2019) analysed the environmental and economic aspects of manufacturing a specific Li-ion battery chemistry. The study emphasised the impact of production volume and electricity mix on eco-efficiency. It was concluded that high production capacity and a low-carbon electricity mix significantly enhance the eco-efficiency of battery manufacturing, with optimized processes potentially reducing climate change impacts to 39.5 kg CO<sub>2</sub> per kWh.

Wolff et al. (2021) combined ecological and economic assessments using a cradle-to-grave approach to evaluate battery and fuel cell electric vehicles. The study found that while battery electric vehicles have a higher environmental impact compared to diesel vehicles with the current electricity mix, the use of renewable energy could reduce this impact by 65%. Additionally, the study indicated that fuel cell vehicles operating with green hydrogen could further decrease environmental impact by 27%, suggesting that advancements in renewable energy and fuel cell technology are crucial for enhancing eco-efficiency.

Despite these valuable insights, there remains a notable gap in comparative studies of eco-efficiency across different electric vehicle technologies using varied methodologies. Few studies have specifically addressed the eco-efficiency of HEVs, PHEVs, and FCHEVs through comprehensive life cycle approaches. This study aims to fill this gap by comparing the eco-efficiency of these vehicle types through multiple methods, including (1) the endpoint damage categories analysis of the vehicle components, (2) the whole-vehicle endpoint damage categories evaluation, and (3) the life cycle cost (LCC) analysis. These methods leverage environmental impact data and life cycle assessment (LCA) using SimaPro to provide a comprehensive evaluation of eco-efficiency. This approach will provide a more detailed understanding of electric vehicle eco-efficiency, offering critical insights for policymakers and industry stakeholders.

## 2 Methodology

A PHEV model, available in Brazil, the United Kingdom, and Spain, along with similar HEV models, was chosen because the same HEV was not available in all countries. The selected HEV and PHEV models are shown in Tables 1 and 2, respectively.

			
Country	United Kingdom	Spain	Brazil
Purchase (US\$) <sup>1, 2</sup>	39,238	26,925	33,194
Brand	Toyota	Toyota	Toyota
Model	Corolla Hybrid Hatchback	Corolla Hybrid Business Hatchback	Corolla Altis Hybrid
Category	1.8	1.8	1.8
Fuel	E10/E5	E10/E5	E27
Power (kW)	72	72	73
Consumption (km/l)	22.69	20.41	15.40
Range (km)	976	878	662
Flex-fuel Technology	No	No	Yes – Ethanol
Power (kW)	-	-	75
Consumption (km/l)	-	-	11.15
Range (km)	-	-	479
Motor Power (kW)	70	70	54
Combined Power(kW)	103	104	91
Battery Capacity (Ah)	4.08	4.08	1.30
Battery Type	Lithium-ion	Lithium-ion	Lithium-ion
CO <sub>2</sub> Emission (gCO <sub>2</sub> /km)	111	111	84
Tank Capacity (l)	43	43	43
Weight (kg)	1,345	1,345	1,440

<sup>1</sup> Purchase values calculated using the conversion factor provided by the Central Bank of Brazil, in July 2024; <sup>2</sup> Incentives for each country were considered.

**Table 1.** Specifications of the HEV for the British, Spanish, and Brazilian scenarios



Country	United Kingdom	Spain	Brazil
Purchase (US\$) <sup>1,2</sup>	77,963	59,410	73,351
Brand		Volvo	
Model		XC60 T8 Recharge	
Category		2.0	
Fuel	E10/E5	E10/E5	E27
Power (kW)	228	228	236
Consumption (km/l)		22.72	
Range (km)		79	
Flex-fuel Technology		No	
Motor Power (kW)		107	
Combined Power (kW)	339	339	345
Battery Capacity (Ah)		14.70	
Battery Type		Lithium-ion	
CO <sub>2</sub> Emission (gCO <sub>2</sub> /km)	23	22	22
Tank Capacity (l)	71	71	70
Weight (kg)		2,170	

<sup>1</sup> Purchase values calculated using the conversion factor provided by the Central Bank of Brazil, in July 2024; <sup>2</sup> Incentives for each country were considered.

**Table 2.** Specifications of the PHEV for the British, Spanish, and Brazilian scenarios

In SimaPro, the simulations of the environmental impacts of electric vehicles were conducted using the ReCiPe 2016 Endpoint (H) V1.07/World (2010) H/A method. For the FCHEV, the Toyota Mirai was selected as it is available in all three countries (UK, Spain, and Brazil). It has a purchase value of US\$ 82,412 – converted by the Central Bank of Brazil (BCB) in July 2024 – and a weight of 1,850 kg, with consistent parameters across all countries. Consequently, only one scenario was applied for the FCHEV in the analysis. The vehicle parameters are presented in Table 3.

Component	HEV	PHEV	FCHEV
Internal Combustion Engine – ICE	7.43%	4.61%	-
Glide and Powertrain <sup>1</sup>	88.59%	91.84%	94.56%
Battery	3.98%	3.55%	2.41%
Fuel Cell Module	-	-	3.03%

<sup>1</sup> The powertrain includes the converter, electric traction motor, inverter, and power distribution unit. Note that the secondary motor coupled to the combustion engine (MG1) was not considered, as its function is solely to start the combustion engine and generate energy for the battery, in addition to having a smaller proportion compared to the electric traction motor. Furthermore, the manufacturer does not specify its size and weight.

**Table 3.** Weight proportions of the main components relative to the vehicle weight

Initially, the endpoint impact categories for the main components were simulated: electric motor, battery, powertrain, and combustion engine. Based on data provided by Toyota and Honda, the average weights of these components were estimated, considering the number of cylinders in the combustion engine and the battery capacity. For example, the combustion engine has an average weight of 25 kg per cylinder, while the battery of the Toyota Prius weighs 53.3 kg, and the battery of a plug-in hybrid vehicle has an average weight of 77 kg for a capacity of 12 kWh (or 14 kWh in the case of the vehicle

analysed in this study). Additionally, the fuel cell of the Mirai weighs 44.6 kg, according to information from Toyota.

The emissions values for the endpoint damage category of the fuel cell were provided by SimaPro per unit. However, it was necessary to calculate the proportion of the fuel cell's weight relative to the total vehicle weight to determine the total emission of the electric vehicle chassis. This was done based on the average weight of the fuel cell provided by Toyota, which is 56 kg. The weight proportions of the components relative to the total vehicle weight are represented in Table 3, and these values were applied to the endpoint damage categories of each component to calculate eco-efficiency.

Eco-efficiency is essentially defined as directly proportional to the economic indicator and inversely proportional to the environmental impact of a particular product (Onat et al., 2019). To calculate the eco-efficiency of the vehicles, different approaches were considered to enable comparisons. Initially, eco-efficiency was calculated as the ratio of the economic value in USD of the vehicle to the environmental impacts of the main components, in Pt/kg. Here, "Pt" stands for "point," which is the total environmental burden expressed as a single score, where characterization, damage assessment, normalization, and weighting are combined. Another approach involved calculating the impact categories of the vehicles, in Pt/kg, considering all endpoint impact categories. Eco-efficiency was then calculated using the ratio between the economic value in US dollars and the endpoint damage category values in Pt/kg.

Eco-efficiency was also calculated considering the LCC, where the calculation represents the sum of maintenance and operation costs over the vehicle's entire lifespan, adopted as the economic value in the numerator of the equation. For vehicles in the United Kingdom, Spain, and Brazil, costs related to the use of E5 gasoline, E10 gasoline, and E27 gasoline, respectively, were applied. This latter method provided a more realistic assessment, reflecting the operational and maintenance costs associated with electric vehicles over their lifecycle. For this analysis, the FCHEV was replaced by a conventional model available in Brazil, the Toyota Corolla, with a purchase value of US\$ 28,690 – conversion performed by the Central Bank of Brazil (BCB) in July 2024 – and a weight of 1,850 kg, allowing for a more comprehensive and contextualized analysis of costs associated with electric vehicles. While the FCHEV represents cutting-edge technology and an innovative alternative to conventional vehicles, its availability and adoption are still limited in many markets, including Brazil. Therefore, by considering a conventional model available in the local market, a more direct and relevant comparison of costs and efficiency of electric vehicles versus traditional vehicles that are widely available and used in the region can be offered. This provides a more practical and applicable view of the economic and environmental viability of electric vehicles in a specific context, contributing to a more complete and informed analysis of the eco-efficiency of these vehicles.

### 3 Results and Discussion

Table 4 presents the damage category values for each component, which represent the environmental impact scores obtained from the endpoint damage categories simulation in SimaPro. Higher values in the table indicate greater environmental damage, while lower values reflect a lower environmental impact.

Eco-efficiency was subsequently calculated based on the total value of each component and is visualised in Figure 1. It is noteworthy that the highest eco-efficiency results were observed in the British PHEV, followed by the Brazilian PHEV, British HEV, and Spanish PHEV. Conversely, the FCHEV exhibited the lowest eco-efficiency, being 55.6% lower than the highest value among the analysed PHEVs and 44.8% lower than the British HEV, which recorded the highest value among the evaluated HEVs.

As highlighted by Onat et al. (2019), eco-efficiency serves as a metric to evaluate sustainability, integrating economic benefits and environmental impacts into a singular measure. A higher amount of

eco-efficiency means less environmental impacts, which is one of the most important factors that determine the value of eco-efficiency. Moreover, it is important to clarify that eco-efficiency, as used in this study, is a relative measure that can be influenced by both an increase in outputs and a reduction in environmental impacts. Eco-efficiency is defined as the ratio between economic value (output) and environmental impacts (input). Thus, an increase in the eco-efficiency index can result from a reduction in environmental impacts, an increase in economic output, or both.

Therefore, a higher eco-efficiency value does not necessarily imply an absolute reduction in environmental impact but rather a more favorable relationship between economic performance and environmental impact relative to outputs. Improving eco-efficiency involves optimizing the relationship between output and input, which can be achieved by increasing productivity or reducing environmental burdens. This relative nature of eco-efficiency should be considered when interpreting the results, as a higher eco-efficiency value indicates a better relationship between economic performance and environmental impacts but does not necessarily denote an absolute decrease in environmental impacts.

The analysis reveals significant variations among the different vehicle types examined: British and Brazilian HEVs demonstrate higher levels of eco-efficiency, while the FCHEV shows the lowest eco-efficiency, indicating higher costs per environmental impact reduction compared to HEVs and PHEVs. Furthermore, the environmental impact of the fuel cell module is 57% and 151% greater than the environmental impacts found for the PHEV and HEV, respectively, resulting in a reduction of its eco-efficiency in USD/Pt. Thus, even though the purchase value of FCHEVs is the highest among the vehicles analysed, the environmental impacts of their life cycle are not sufficiently reduced to achieve high eco-efficiency. Therefore, it is important to develop more efficient technologies for the manufacture of fuel cell modules, as well as more abundant and less polluting materials, to reduce the negative impacts of their production.

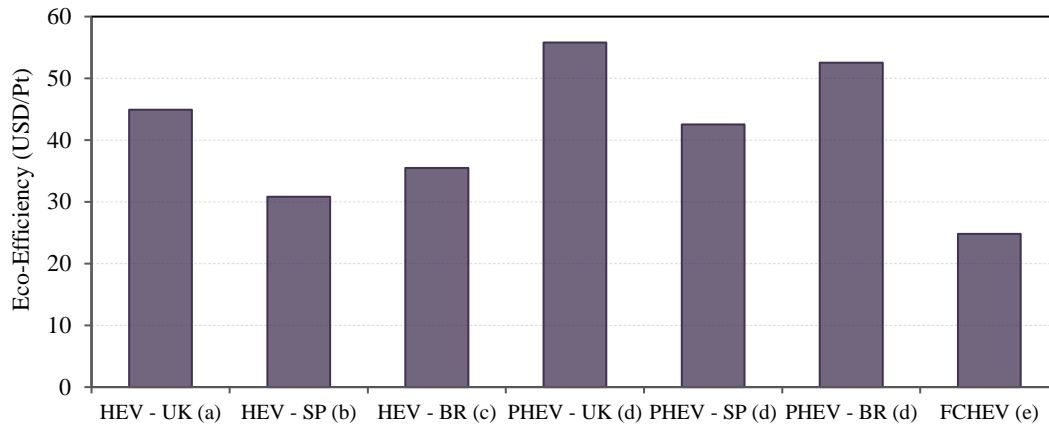
PHEVs stand out for superior eco-efficiency in both the UK and Brazil, surpassing all evaluated HEV variants. This is a result of their high purchase value, nearly twice that of HEVs, which is offset by their environmental impact, 60% greater than that of HEVs, leading to an eco-efficiency up to 48% higher than HEVs. Particularly, British vehicles exhibit the highest eco-efficiency due to their higher purchase value among the PHEVs and HEVs analysed.

These findings underscore the importance of considering not only direct costs but also environmental impacts when assessing vehicle eco-efficiency. Encouraging the adoption of vehicles with proven eco-efficiency metrics can drive significant environmental gains while enhancing economic sustainability in the automotive sector.

Damage Category	Glide and Powertrain <sup>1</sup>	ICE <sup>1</sup>	Battery <sup>1</sup>	Fuel Cell Module <sup>2</sup>
Human Health	0.5900	0.6370	1.5700	2.7970
Ecosystems	0.0117	0.0150	0.0367	0.0634
Resources	0.0036	0.0042	0.0130	0.0208
Total	0.6053	0.6562	1.6197	2.8812

<sup>1</sup> Found in Pt per kilogram of vehicle, requiring multiplication by the vehicle's weight; <sup>2</sup> Found in Pt per piece of fuel cell module.

**Table 4.** Values found for endpoint damage categories for each main component



(a) Toyota Corolla Hybrid Hatchback; (b) Toyota Corolla Hybrid Hatchback Business; (c) Toyota Corolla Altis Hybrid; (d) Volvo XC60 Recharge; (e) Toyota Mirai

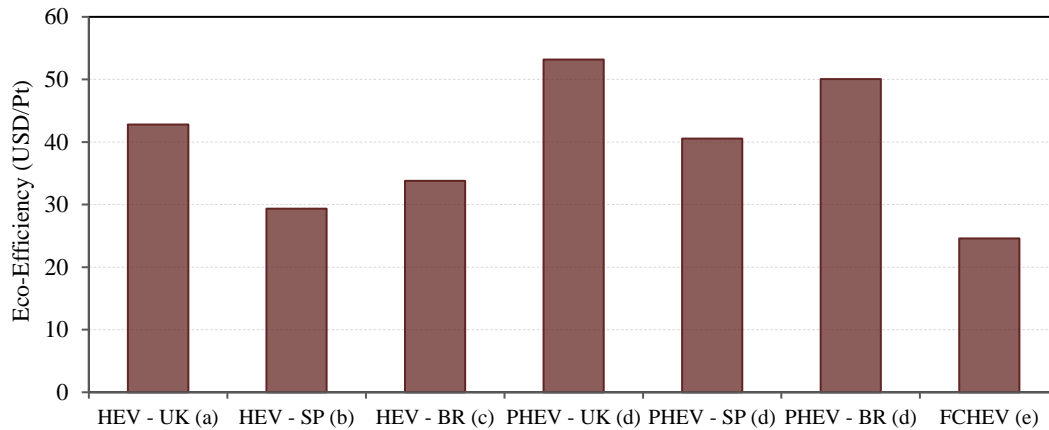
**Figure 1.** Eco-efficiency values for different types of electric vehicles analysed, calculated based on total environmental impacts and the main components of the vehicles (Method 1)

When using the damage category values for the vehicles (Table 5), the eco-efficiency values were found to be very close to those calculated using the main components and their weight proportions in each vehicle. Figure 2 displays the eco-efficiency values found for each type of vehicle analysed. The results for HEVs were 4.79% lower than those found in the previous method, while PHEVs and FCHEVs were 4.72% and 0.86% lower, respectively. This minimal difference suggests that considering the impact categories of the vehicles does not significantly alter the assessment of eco-efficiency compared to the previous method. This indicates consistency in the results, regardless of the approach used, which strengthens the robustness of the conclusions reached.

Damage Category	PHEV <sup>1</sup>	HEV <sup>1</sup>	FCHEV <sup>1</sup>
Human Health	0.6574	0.6637	0.6110
Ecosystems	0.0141	0.0143	0.0123
Resources	0.0040	0.0041	0.0038
Total	0.6755	0.6821	0.6271

<sup>1</sup> Found in Pt per kilogram of vehicle, requiring multiplication by the vehicle's weight.

**Table 5.** Values found for endpoint damage categories for each type of vehicle



**Figure 2.** Eco-efficiency values for different types of electric vehicles analysed, calculated based on total environmental impacts and considering the vehicle (Method 2)

Values found for endpoint damage categories for each main component were calculated using a third method that utilises life cycle cost (LCC) as an economic indicator (see Table 6), simplifying results for comparative purposes. The resulting eco-efficiency values can be seen in Figure 3. Notably, values found for HEV and PHEV were higher than those obtained in other methods, as all operation and maintenance costs were considered. These results underscore the importance of considering all costs associated with operation and maintenance when evaluating the eco-efficiency of electric vehicles, providing a more comprehensive and accurate view of their environmental and economic performance.

The results show that HEVs and PHEVs exhibit significantly higher eco-efficiency values compared to the chosen conventional model, indicating not only a lower environmental footprint per unit cost but also potentially significant lifecycle savings. When compared with the chosen conventional model, HEVs showed values up to 31.34% higher, while PHEVs can exhibit a difference of up to 74% higher.

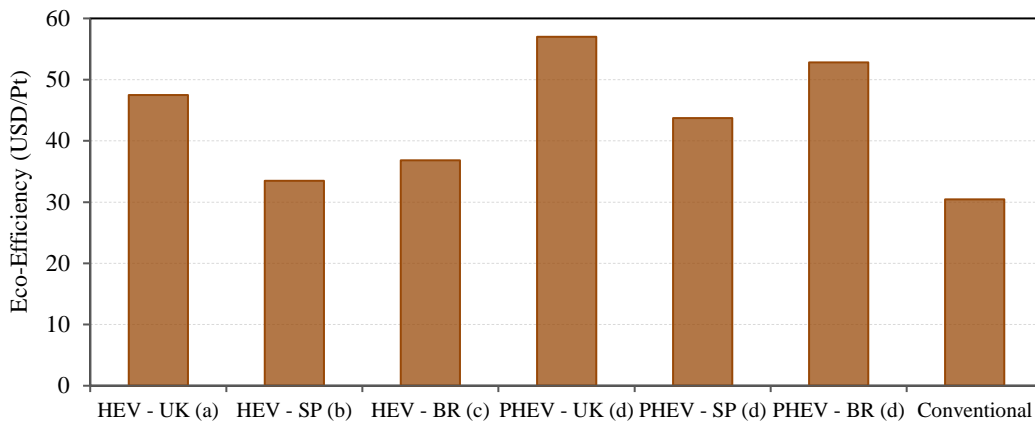
Although it is difficult to compare technologies, as noted by Wolff et al. (2021), comparing the eco-efficiencies of PHEVs and HEVs provided a clearer view that HEVs, particularly the Brazilian HEV, achieve favourable eco-efficiency with median LCC values, 26% higher than the chosen conventional Brazilian vehicle, and with lower environmental impact compared to PHEVs.

The analysis highlights the robustness of the LCC method in capturing both direct and indirect costs, including operation, maintenance, and eventual component replacement. This approach is crucial for guiding policy decisions and business strategies towards adopting more sustainable and economically viable automotive technologies.

Vehicle - Country	LCC (US\$)
HEV – United Kingdom <sup>a</sup>	40,958
HEV - Spain <sup>b</sup>	30,523
HEV - Brazil <sup>c</sup>	40,487
PHEV – United Kingdom <sup>d</sup>	79,332
PHEV - Spain <sup>d</sup>	63,730
PHEV - Brazil <sup>d</sup>	86,657
Conventional <sup>e</sup>	32,057

(a) Toyota Corolla Hybrid Hatchback; (b) Toyota Corolla Hybrid Hatchback Business; (c) Toyota Corolla Altis Hybrid; (d) Volvo XC60 Recharge; (e) Toyota Corolla

**Table 6.** Average LCC values found for the types of vehicles analysed in each scenario



**Figure 3.** Values of eco-efficiency for different types of electric vehicles analysed, calculated considering the LCC, compared to the conventional vehicle (Method 3)

## 4 Conclusions

In this study we employed three distinct methodologies to assess the eco-efficiency of EVs: analysis of endpoint damage categories for major components, evaluation of whole-vehicle endpoint damage categories, and LCC analysis as an economic indicator. Each method has provided valuable findings regarding the sustainability performance of EVs.

The results underscore significant eco-efficiency advantages for HEVs and PHEVs over conventional models. HEVs demonstrated eco-efficiencies up to 31.34% higher, and PHEVs showed up to 74% higher eco-efficiency compared to the conventional model used for comparison. Regional differences also emerged, with the British and Spanish markets exhibiting particularly opposite eco-efficiency performances due to their highest and lowest acquisition values, respectively. Conversely, the FCHEV consistently showed the lowest eco-efficiency values across all methodologies, highlighting current challenges in market adoption and operational efficiency.

It is important to acknowledge that the choice of indicators for input and output in the eco-efficiency analysis can significantly influence the results. In this study, we used endpoint damage categories and LCC analysis as our primary indicators. The selection of these indicators, while comprehensive, may affect the interpretation of eco-efficiency and sustainability. The normalization of damage category

values and the weighting of economic factors, for instance, could impact the comparative results between vehicle types. Additionally, the exclusion of certain advanced technologies, such as FCHEVs, from some of the analyses due to limited adoption in specific regions may also introduce constraints in the overall assessment. Future research could benefit from exploring alternative indicators and incorporating a wider range of technologies to enhance the robustness and generalizability of eco-efficiency evaluations.

These findings emphasize the importance of comprehensive assessments that integrate economic indicators and environmental impacts in evaluating EV sustainability. Such evaluations are essential for informing future advancements in automotive technology and policy to promote more sustainable transportation solutions globally.

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# Carbon policies and electric vehicles: a systematic review of the main strategies

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## Abstract

This paper provides a systematic review of the role of electric vehicles in carbon regulation policies in order to reduce the CO<sub>2</sub> emissions of the transport sector. For that purpose, the systematic review was conducted by following the PRISMA protocol, with research carried out through the Web of Science and Scopus databases. The results reveal the novelty of the carbon policies and growing tendency. Most of the studies were developed by China (66 out of 187 (co)authors) and USA (with 47 (co)authors). The policy addressed the most in the papers were carbon tax (in 37 articles), followed by cap-and-trade (12 articles) and carbon cap (3 articles) and some articles deal with more than one carbon policy. The papers majority deal with the replacement of internal combustion vehicles by hybrid and fully electric vehicles. Another relevant approach is related to the electric vehicle batteries (autonomy, charging/recharging process, and reuse/disposal). The limitations are related to costs (fleet change, implementation of charging locations, prices variation and so on). Despite that, the adoption of EVs could help in the reduction of CO<sub>2</sub> in the long term, especially if combined with cleaner energy sources. The article highlights positive and suggestive points for researchers on the subject.

Keywords: Carbon Policies, Transport, Electric Vehicle, Carbon Emission.

## 1 Introduction

Driven by the increasing demand for passenger and freight transport associated with changes in the consumption pattern of modern society (as online shopping), the transportation sector had become one of the main responsible for the global emissions of greenhouse gases (GHGs). About 90% of the worldwide transportation sector uses fossil fuels as main source of energy and apart from the climate change, it faces another environmental issue: the scarcity and depletion of the fossil fuels as a natural resource (MandaL; Cho, 2022). Therefore, governments and manufacturers are trying to shift towards less polluting vehicles, while developing ecofriendly policies applied to this sector. According to the [R]evolution Energy Report from Greenpeace<sup>28</sup>, technologies that allow the use of electricity as a source of energy will be fundamental to abdicate fossil fuels (Teske et al., 2010). It explains why electric vehicles - EVs has gained more space within the industry: EVs have zero GHGs emission and do not use fossil fuels during its operation (Valta et al., 2018; Zhang et al., 2019) – although there is a large discussion regarding the sources used to produce energy to move the EVs. Beyond the EVs,

governments all over the world have been joint efforts in reducing emissions, by the development of their own carbon polices. According to ICAP (2024) direct carbon pricing instruments (taxes or markets) aimed at internalizing the external costs of carbon emissions. In this sense, *“they are designed to create economic incentives for reducing greenhouse gas emissions and transitioning towards a low-carbon economy”* (ICAP, 2024).

The ICAP report (2024) shows that there are 36 systems in force around the world, with another 22 at various stages of consideration and development. The policies vary from carbon tax to emission-trading schemes and cover 18% of GHG emissions worldwide (ICAP, 2024). Nevertheless, most of them do not covers the transport sector. Therefore, other types of strategies that help this sector to reduce its carbon footprint becomes even more relevant, even though it is not under regulation yet. One might realize that the carbon markets might become an opportunity for those more carbon efficient that might be able to sell their carbon credits. In this sense, the carbon policies might help in incentivizing project aiming at reducing the energy usage (specially from fossil sources) and at developing “cleaner” technologies. Regarding the cleaner technologies, one promising strategy found on the literature is the adoption of electric vehicles (despite the issues related to the source of energy and social impacts of miner exploitation).

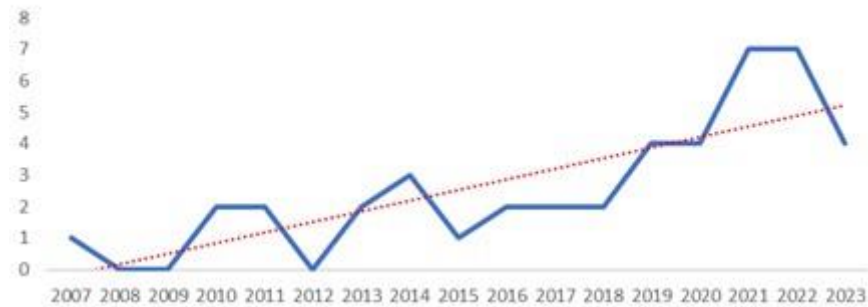
In this context, this paper provides an overview of the role of the electric vehicles in the carbon regulation policies related to the transport sector. A systematic review of the literature published in Web of Science and Scopus database was performed following the PRISMA protocol. Criteria like the type of carbon policy, emphasis on the role of the electric vehicle and limitations on the small-scale electric vehicle were also addressed. From this introduction, this paper presents the methodological procedures; and, main findings. Lastly, we have the acknowledgments and references.

## 2 Methodology

A systematic review was conducted by following the PRISMA protocol to the data gathered from Web of Science and Scopus databases. Only articles published in scientific journals (in English) were considered, from 1945 to 2023 years. The keywords were: TS= (“electric vehicl\*” or “electric car\*” or “recharg\* station” or “charg\* station” or “battery”) AND (“carbon cap” or “carbon trade” or “carbon cap-and-trade” or “carbon tax” or “emission trad\* system” or “carbon regulation \*” or “carbon-and-invest\*” or “personal trad\*” or “baseline-and-credit”) AND “transport\*”. They were chosen to identify the different dimensions related to the electric vehicle, but from the transportation point of view. Different types regulation policies were considered. Therefore, 53 results were found in WOS and 67 in Scopus, with 120 as total records tracked. After identifying 49 duplicates, the records dropped to 71 eligible. Once the contents were read, only 43 results were selected for meta-analysis.

## 3 Findings

Although no initial time frame was imposed in the search, the first article about the subject was published only in 2007, which can be related to the novelty of the own carbon policies – EU ETS is from 2005, e.g. Despite the variation on the publication of the 43 eligible articles by year, the red line in Figure 1 show a growth tendency. This tendency can be explained by the growth of the electric vehicle segment – which new players as Tesla and BYD – as well as new governmental policies to leverage the adoption of electric vehicles (see IEA, 2021).



**Figure 1:** Distribution of the publications over the year

Regarding the distribution of papers per country, most of the studies were developed by China (66 out of 187 (co)authors) and USA (with 47 (co)authors). It is important to highlight that both countries already have carbon markets in force. The USA have a well-established carbon market operating since 2005: The Regional Greenhouse Gas Initiative – RGGI, but it does not cover all the USA territory neither includes the transport sector. The Washington cap-and-invest program is in force since 2023 covering transport sector, but restricted to the state (ICAP, 2024). China also have carbon markets in force, as China National Emissions Trading System from 2021 (that do not include the transport sector), besides other pilots around the country (e.g. Beijing and Guandong that include transport and aviation, respectively).

Table 1 summarize the role of the EVs in the carbon policy studied in each article, as well as the limitations regarding the adoption of the EVs. The policy addressed the most in the papers were carbon tax (in 37 articles), followed by cap-and-trade (12 articles) and carbon cap (3 articles)-Note that some articles deal with more than one carbon policy.

Reference (year)	Carbon policy	Role of EV	Limitations
Zhao, Y.; Noori, M; Tata ri, O. (2016)	Tax	Replacement: current diesel trucks to electric batteries until 2030 and its impact on GHG.	Fuel replacement cost
Bhardwaj, C. et al. (2020)	Tax	Charging: infrastructure.	Cost-benefit
Li, W. et al. (2019)	Cap and Trade/Tax	Replacement-conventional fuel vehicles to (BEVs).	Cost-benefit
Xiang, Y. et al. (2021)	Tax	Battery-Charging/discharging	Battery charging time
Fridstrøm, L. (2021)	Cap and trade	Replacement : market acceptance of battery electric and hybrid cars in Norway	Implementation cost.
Liu, X.; Wang, N.; Dong, D. A (2018)	Tax	Battery: Charging or swapping (New vehicle type).	Operational cost of the electric taxi system and utilization rate of charging facilities

Reference (year)	Carbon policy	Role of EV	Limitations
Li, Y. et al. (2020).	Tax	Battery - charging stations	Environmental, sustainability and cost balance
Paltsev, S. et al. (2018)	Tax	Battery - Charging	Operational, handling, and environmental energy costs
Shafiei, E. et al. (2014)	Tax	Replacement-Battery replacement (cost and size)	Cost of electric vehicle application (both vehicle replacement and overall battery-related costs)
Karplus, V. J.; Paltsev, S.; Reilly, J. M. (2010)	Cap and trade	Replacement - hybrid electric vehicles	Adaptation to changes. Dependence on Coal Power and Rising Electricity Demand.
Popiolek, N.; Thais, F. (2016)	Tax	Charging - Charging point Replacement - Transition to electric vehicles	Implementation costs, charging points and electric vehicles transition
Li, B. et al. (2022)	Cap	Battery - Autonomy, charging time. Comparison - Variety of fuels for road vehicles	Batteries Costs
Pietzcker, R. C. et al. (2014)	Tax	Replacement - Shift to plug-in hybrids, battery electric vehicles, or fuel cell vehicles	Initial investment cost for vehicle transition
Linn, J.; Mcconnell, V. (2019)	Cap and trade/Tax	Replacement - Replace combustion vehicles with hybrid and/or hydrogen storage electric vehicles. Battery: Production cost/performance	federal and state policies
Watabe, A. et al. (2019)	Tax	Replacement - Transition to BEVs, hydrogen fuel cell vehicles, and natural gas vehicles. Battery - Charging stations, replacement cost, autonomy	Initial implementation costs, with positive value for batteries around 2029
Lokey, E. (2007)	Tax	Replacement -hybrid and plug-in electric vehicles in the transport sector to transfer liquid fuel requirements to the electric grid	Initial costs for these changes and the energy demand by electric vehicles
Hu, X. et al. (2021)	Tax	Comparison/Replacement– comparison of conventional cars with battery electric cars in different scenarios	users' acceptance

Reference (year)	Carbon policy	Role of EV	Limitations
Shafiei, E. et al. (2017)	Tax	Comparison / Replacement - Analyze different vehicle fuel types, inducing the shift to electric vehicles	Incentive: Accelerated transition to hydrogen and electric vehicles through strict policies banning gasoline and diesel vehicles from 2035
Dowds, J. et al. (2010)	Cap and trade	Battery - Charging demand (night charging), autonomy, capacity. Hybrid vehicles present higher charging demand	Energy cost
Dowds, J.; Hines, P. D. H.; Blumsack, S. (2013)	Cap and trade	Charging - Electricity demand for charging electric vehicles	Charging cost. Suggest balancing with wind energy for electric vehicle charging
Tulpule, P. J. et al. (2013)	Tax	Charging - Electric vehicle charging station Battery - Charging capacity	Installation cost of photovoltaic panels, maintenance cost, financing cost, electric vehicle battery capacity
Figliozzi, M. A.; Boudart, J. A.; Feng, W. (2011)	Cap-and-trade/Tax	Comparison/Replacement: Demonstrate the "right time" for electric vehicle adoption to avoid high costs	Cost
Jones, E. C.; Leibowitz, B. D. (2019)	Tax	Utilization - Use of shared autonomous vehicle models. Comparison - Different vehicles. Battery - Autonomy	Individual adoption for shared autonomous vehicles
Hao, H. et al. (2017)	Tax	Utilization - Benefits for carbon emission reduction	Low autonomy and long charging time and Costs Application of new batteries
Creutzig, F. et al. (2011)	Cap-and-trade/Tax	Utilization - How the behavior occurs when using electric vehicles (Battery electric vehicles (BEVs), fuel cell hybrid electric vehicles and electric bicycles)	Energy prices, battery technology/cost, economies of scale, charging infrastructure, regulatory requirements and tax incentives.
Yagcitek, B. et al. (2015)	Cap and trade	Utilization - Electric vehicle use in Istanbul	Lack of approach to the production/consumption relationship between energy and electric vehicle utilization

Reference (year)	Carbon policy	Role of EV	Limitations
Lindsey, R.; Santos, G. (2020)	Cap-and-trade/Tax	Utilization - battery demand, utilization, combustion vehicle replacement, (advantages and disadvantages)	Fiscal incentives. User acceptance. Cost. Energy generation dependency.
Tang, J. et al. (2014)	Tax	Battery - Charging time (recharge), battery replacement: (different models), autonomy	Initial short-term cost
Wang, B. et al. (2021)	Tax	Comparison -compares best adoption between gasoline, hybrid plug-in, and electric vehicles	Individuals prefer hybrid vehicles over electric vehicles
Zhu, X. et al. (2021)	Cap-and-trade/Tax	Comparison - Between electric vehicles and gasoline	High production costs. Consumer recognition
Li, B. et al. (2021)	Cap	Utilization/Performance - Levels of electric vehicle adoption, smart charging participation rate, and carbon emission restrictions	Energy demand for electric vehicles
Long, Z.; Kitt, S.; Axsen, J. (2021)	Cap-and-trade/Tax	Comparison-Questionnaire considering internal combustion, hybrid, and electric vehicles	No significant limitation data on non-use
Wang, L.; Wang, X.; Yang, W. (2020)	Tax	Battery:recycling, remanufacturing, disposal	Recycling cost
Wang et al., (2022)	Tax	Battery - Load capacity, battery capacity	Batteries Costs
Wang et al., (2023)	Tax	Replacement - electric bus fleets	Acquisition. cost/ adapting old fleets cost
Zhou et al. (2022)	Tax	Battery - Difficult electrification for ferries and freight transport due to size and costs	Batteries Costs
Abdullah-AL-Nahid et al. (2023)	Tax	Comparison/Replacement - Compare electric vehicles with other vehicle models and encourage electric vehicle adoption	Manufacturing/battery costs.
Wang et al. (2022)	Tax	Battery - Charging autonomy	Battery Costs
Aryanpur et al. (2022)	Tax	Comparison/Replacement: Comparison of current passenger and collective vehicles and fuels with electric vehicles	Initial adoption cost
Li; Li; Jenn (2022)	Tax	Comparison -vehicles with shared autonomous electric vehicles/ Battery - Charging, autonomy	Costs/Travel time, financial adaptation, initial adaptation
Achariyaviriya et al. (2023)	Tax	Comparison - Between internal combustion and electric vehicles	Battery cost/ capacity

Reference (year)	Carbon policy	Role of EV	Limitations
Yan; Ding; Chen (2023)	Tax	Economic viability -electric vehicle users and manufacturers	Government incentives and regulations
Ercan et al. (2022)	Tax	Comparison-potential environmental impacts of public transport options, ride-sharing, walking, cycling, and various transport policy applications	Alternative transport Encouragement and current dependency on conventional.

**Table 1:** Data of selected articles

One may note that carbon tax is the main carbon police considered although carbon cap-and-trade (also known as emission trading system - ETS) are the policy implemented the most around the world. According to ICAP 2024 (2023), as of January 2024, there are 36 ETS in force and 14 under development. Nevertheless, World Bank (2023) point that there are 70 carbon pricing initiatives, among ETS and carbon tax. We believe that the higher number of papers about carbon tax are related to two main factors: (i) it is harsher to evaluate all the aspects of an ETS, since it would have to deal with carbon leakage, baking and borrowing, auditions allowances and so on; (ii) carbon tax can be studied as a step toward the carbon market.

Regarding the role of the electric vehicle in this context, most of the papers deal with the replacement of internal combustion vehicles by hybrid and fully electric vehicles. Another relevant approach is related to the electric vehicle batteries, involving studies about their autonomy, charging/recharging process, and their reuse/disposal in the best possible way, as seen in Wang et al. (2020).

The limitations for electric vehicles large scale implementation, in general, are related to the costs (fleet change, implementation of charging locations, prices variation due to greater demand for power generation and so on). Despite the initial costs of electric vehicles' implementation in large scale, several authors point out that the adoption of EVs could help in the reduction of CO<sub>2</sub> in the long term, especially if it is combined with cleaner energy sources (for instance, wind and solar). In addition, there already are governmental incentives to stimulate the fleet change. In 2021, Joe Biden, former US president, set the goal that 50% of all cars sold in the US in 2030 will be electric. The European Union has presented measures, not yet approved, to ban the sale of combustion cars from the year 2035 (see IEA, 2021 and Verneque et al 2020). In Brazil, there are programs such as Rota 2030 to encourage the energy transition in the transport sector (Alves, Frascino e Chimelli, 2022).

## 4 Final considerations

EVs allied to carbon pricing policies are a promise combination to help in decarbonizing the transport sector. Therefore, this paper fulfill its main goal by providing a systematic review of the role of electric vehicles role in carbon regulation policies. The first result article was published only in 2007, revealing the novelty of the carbon policies and growing tendency. This can be explained by the growth of the electric vehicle segment as well as new governmental policies to leverage the adoption of electric vehicles. Most of the studies were developed by China (66 out of 187 (co)authors) and USA (with 47 (co)authors). The policy addressed the most in the papers were carbon tax (in 37 articles), followed by cap-and-trade (12 articles) and carbon cap (3 articles) and some articles deal with more than one carbon policy. Regarding the role of the electric vehicle, most of the papers deal with the replacement of internal combustion vehicles by hybrid and fully electric vehicles. Another relevant approach is related to the electric vehicle batteries, involving studies about their autonomy, charging/recharging process,

and their reuse/disposal in the best way. The limitations for electric vehicles are related to the costs (fleet change, implementation of charging locations, prices variation due to greater demand for power generation and so on). Despite the initial costs of electric vehicles' implementation in large scale, several authors point out CO<sub>2</sub> reduction., especially combined with cleaner energy sources. With these findings, researchers can get a better understanding and direction for suggestive future steps, for example, in choosing the journal and in the search for international partnerships, which would facilitate the consolidation and approval of future articles. The limitation of this paper is related to the limitation of the systematic review itself (keywords and database selection). As future researches, articles can dive in the relation of the carbon policies of each country as well as the existence (or not) of policies incentivizing the adoption of EVs. Studies focused on the Brazilian context are encourage since there are other sources of clean fuels and, therefore, other potential carbon mitigation strategies then EVs.

## Acknowledgements

The authors thanks CAPES - Code 001 and PR2 – UFRJ - ALV 2023.

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# Analysis of the Integration of Sustainability Education in the Engineering Curriculum at a Federal Educational Institution in Brazil

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## Abstract

This study examines the incorporation of the sustainability concept into the curriculum of engineering courses at a campus of a Brazilian public university, emphasizing the growing importance of training professionals to address sustainability challenges. The research involved interviews with course coordinators and an analysis of academic documents. Findings reveal that, despite acknowledging the importance of sustainability, its integration into engineering curricula remains superficial and fragmented, with relevant content often confined to isolated courses. The study identifies significant challenges, including resistance to change, resource scarcity, and a lack of an organizational culture that values sustainability. To address these issues, the article proposes a comprehensive curriculum revision that promotes integration and the implementation of extension and research projects focused on sustainability. Collaboration among all academic community members is essential to transforming engineering education, preparing students to become agents of change, and contributing to sustainable development.

Keywords: sustainability, university, curriculum, engineering.

## 1 Introduction

The inclusion of sustainability in higher education has become an increasingly important topic, highlighting the urgency of preparing young people for global environmental, social, and economic challenges. Sustainability, defined as development that meets current demands without compromising the ability of future generations to meet their own needs (WCED, 1987), is a crucial principle across various sectors, including education.

Since the 1980s, the concept of sustainability has gained prominence following the publication of the Brundtland Report, which emphasizes the integration of economic growth, social justice, and environmental protection (WCED, 1987). In higher education, this perspective is evident in the

incorporation of sustainable principles into academic programs, teaching methods, and institutional management. Sustainability is not merely a subject of study; it is a practice that shapes the future of educational institutions and the training of professionals to promote sustainable development (Desha & Hargroves, 2021).

The concern with sustainability in engineering is of utmost importance, considering the crucial role this field plays in seeking solutions to environmental and social issues. Integrating sustainability into engineering education programs not only prepares students to address complex challenges but also fosters innovation and social awareness (Mihelcic et al., 2018). In this context, it becomes relevant to investigate how the universities are dealing with sustainability in the academic context, especially with concern to its inclusion in curricula. Different papers have been seeking to understand how universities are adopting sustainability principles in their practices and academic programs and to identify the main challenges and best practices encountered in this integration process (Sánchez-Carracedo et al., 2019. Trad, 2019. Leifler et al., 2020. Akeel, 2019. Idoiaga Mondragon et al., 2024).

This study analyzes whether and how the concept of sustainability has been incorporated into the curriculum of engineering courses offered by a campus of a Brazilian public university, given the growing importance of training professionals capable of addressing sustainability challenges. Investigating the implementation of sustainability in higher education is crucial to ensure that future engineers are equipped with the knowledge and skills necessary to contribute to a more sustainable future.

From this Introduction, this paper is divided into three sections: a literature review of sustainability and engineering, methodology and main findings.

## 2 Literature Review

The importance of sustainability in the Engineering area is evident since it can directly impact the results of projects, methods to be used, and systems to be adopted to reduce environmental damage, promote economic results, and ensure social equity. Engineering professionals can play a crucial role in developing solutions aimed at reducing pollution, preserving natural resources, and protecting ecosystems. As highlighted by Mihelcic et al. (2018), adopting sustainable practices in engineering can result in significant reductions in environmental impacts and the preservation of natural resources. The adoption of measures aimed at sustainability in engineering not only contributes to long-term savings but also opens new business opportunities.

According to Boks and Diehl (2018), incorporating sustainable practices can reduce operational costs and generate economic value by stimulating innovation and efficiency. Byrne, Desha, and Fitzpatrick (2019) emphasize that including viable principles in engineering can improve living standards and ensure that projects do not harm vulnerable communities. Sustainability also stimulates technological creativity, promoting the development of new technologies such as clean energy sources and environmentally friendly materials. It is important to mention that sustainability goes beyond environmental performance, also addressing potential economic advantages and the social agenda.

According to Desha and Hargroves (2021), sustainability plays a crucial role in generating technological advancements and challenging professionals to seek more effective and environmentally respectful solutions. These innovations are essential to address future challenges and ensure sustainable progress. Additionally, compliance with environmental laws and regulations is essential for the image

and competitive position of organizations. Porter and Kramer (2019) discuss how implementing sustainable actions can strengthen a business's reputation and increase competitiveness on an international level. Therefore, engineering education plays a fundamental role in promoting sustainability. According to Sterling (2020), including sustainable topics in engineering programs prepares future professionals to address environmental and social issues, encouraging the adoption of more sustainable practices in all project stages.

Sustainability in higher education aims to incorporate sustainable development principles into academic programs, teaching strategies, research, and management of educational institutions. Sterling (2020) argues that education should adopt a comprehensive approach to sustainability, integrating it into all disciplines and teaching methods.

Desha and Hargroves (2021) highlight the relevance of using active methodologies, such as practical projects and case studies, to engage students in applying sustainability concepts. Moreover, academic study needs to focus on environmental and societal themes, seeking to create new ideas that can contribute to sustainable solutions (Mihelcic et al., 2018).

Therefore, universities should incorporate sustainable management methods and promote a mindset oriented toward environmental and social responsibility (Boks & Diehl, 2018). Developing conscious individuals is a fundamental goal, preparing students to be positive agents in the community and address global issues (Byrne, Desha & Fitzpatrick, 2019). Despite challenges such as a lack of resources and resistance to change, incorporating sustainability brings possibilities for innovation and creating new forms of education (Mulder, 2018).

### 3 Methodology

The study was conducted at a prestigious federal institution with over a century of experience in the educational field, located in the state of Rio de Janeiro. With a solid reputation for academic and research excellence, the institution stands out for its innovative proposals and the competence of its faculty, composed of specialized professionals, masters, doctors, and post-doctorates recognized in various fields of knowledge. Additionally, it boasts a high-quality infrastructure, including laboratories, well-structured libraries, and advanced research centers, providing a conducive environment for scientific progress and cutting-edge academic investigation.

To analyze the inclusion of sustainability education in the Engineering curriculum of the federal institution in question, a qualitative approach was adopted. The process phases involved:

- Interviews (field research): Conducted with the coordinators of the Mechanical, Electrical, and Metallurgical Engineering courses to obtain their opinions on the integration of sustainability in the teaching plans and find examples of good practices implemented. It is important to highlight that all course coordinators are highly qualified professionals, each holding a doctorate and having extensive research experience. Each of them has more than 8 years of dedication to the institution, contributing significantly to its academic development. Additionally, they have a rich professional background in their respective fields, bringing a valuable combination of academic knowledge and practical experience.

The following questions were asked during the interviews:

1. What is your view on including sustainability education in the engineering curriculum?

2. Is the concept of sustainability mentioned in the PPC - Pedagogical Project of the Engineering course?
  3. How is sustainability currently integrated into the engineering course subjects? Which subjects address this theme?
  4. What are the main challenges you might face when integrating sustainability into the engineering curriculum?
  5. What kind of support (resources, training, institutional policies) do you consider necessary to improve the inclusion of sustainability in the course?
  6. What changes or improvements would you like to see in the engineering curriculum to strengthen the inclusion of sustainability?
  7. Suggestions for improving the approach to sustainability in the engineering course.
  8. Lastly, do you know if any research or extension projects related to sustainability are being developed in your department? I think this could help, in some way, improve the approach to sustainability in the curriculum.
  9. How is sustainability currently integrated into the engineering course subjects? Which subjects address this theme?
  10. What are the main challenges you might face when integrating sustainability into the engineering curriculum?
  11. What kind of support (resources, training, institutional policies) do you consider necessary to improve the inclusion of sustainability in the course?
  12. What changes or improvements would you like to see in the engineering curriculum to strengthen the inclusion of sustainability?
  13. Suggestions for improving the approach to sustainability in the engineering course.
  14. Lastly, do you know if any research or extension projects related to sustainability are being developed in your department? I think this could help, in some way, improve the approach to sustainability in the curriculum.
- Document Analysis: Conducted a review of important documents, such as syllabi, study plans, and Course Pedagogical Projects (CPP), to identify if and how the sustainability concept was being addressed, as well as if there were any other activities/projects that could be addressing the sustainability concept, even if it was not clearly offered during the course. It is worth mentioning that the PPC for the degree in mechanical engineering underwent an update in 2020, while that for metallurgical engineering was revised in 2018 and that for electrical engineering in 2022.
  - Information Collection and Structuring: The data collected during the interviews and document analysis were systematized to simplify the identification of gaps, problems, and opportunities for improvement in the implementation of sustainability. In July 2024, a total of 8 questions were asked during the interview, aiming to understand the extent of the coordinators' commitment to integrating sustainability into the engineering curriculum and the relevance each of them attributed to this topic. It was identified that courses such as Projects in Electrical Engineering, Final Project, State,

Market and Society, and Environmental Sciences mention the topic of sustainability.

Through this procedure, it was possible to obtain a broad understanding of the current situation of the inclusion of sustainability in Engineering.

## 4 Data Analysis Type

The data analysis conducted in this study is qualitative, focusing on understanding the integration of sustainability education in engineering curricula. The analysis process involved two main approaches:

- Qualitative Interviews.
- Document Analysis.

The combination of these two approaches provided a comprehensive view of the current state of sustainability education in engineering programs, enabling the identification of gaps, challenges, and opportunities for improvement in integrating this crucial topic.

## 5 Data Analysis

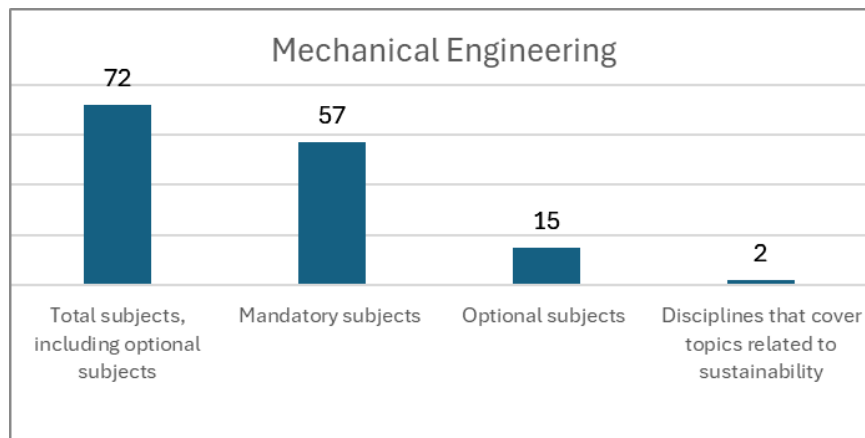
The analysis of the collected data revealed that the approach to sustainability in the curricular documents of Metallurgical, Electrical, and Mechanical Engineering courses of the university under assessment is largely fragmented and superficial. The contents related to sustainability tend to be treated as isolated subjects, with little integration and connection between them and other strategies present in the curriculum.

A detailed analysis of the syllabi and the pedagogical project of the Mechanical Engineering course, in Figure 1, has brought to light important information about the inclusion of sustainability topics in the curriculum. The graph represented in Figure 1 summarizes the collected data, offering a clear and precise view of the distribution of required and elective courses, as well as the presence of sustainability-related content. Out of the 72 available courses in the program, 57 are mandatory, forming the majority of the curriculum, while 15 are elective, allowing students some freedom in choosing their areas of interest. However, only two courses mention sustainability, representing just 2.77% of the total number of courses offered.

This result points to a potential gap in the education of future mechanical engineers regarding the understanding and application of sustainable principles (Aleixo et al., 2020). This highlights the urgency to increase the focus on sustainability in the Mechanical Engineering curriculum. According to Iyer-Raniga & Andamon (2018), when environmental concerns and sustainability are increasingly prominent in engineering and other fields, it is essential to include more courses that address these topics. This review would not only align the course with current market and societal demands but also prepare students for future challenges with a more comprehensive and responsible perspective.

This integration can be achieved by revising existing syllabi to include sustainability aspects, creating new courses focused on this topic, or incorporating sustainability-related content (Lozano et al., 2019). Additionally, promoting interdisciplinary projects that emphasize sustainability can provide students with a practical and applied understanding of these concepts (Lambrechts et al., 2019). Therefore, the need for curriculum reform is evident. The course administration and those responsible for the pedagogical project should consider this evidence and work towards creating a curriculum more aligned with contemporary demands, preparing mechanical engineers who are conscious and ready to contribute to a sustainable future (Leal Filho et al., 2022). The mechanical engineering PPC is in the latest version, updated in 2020.

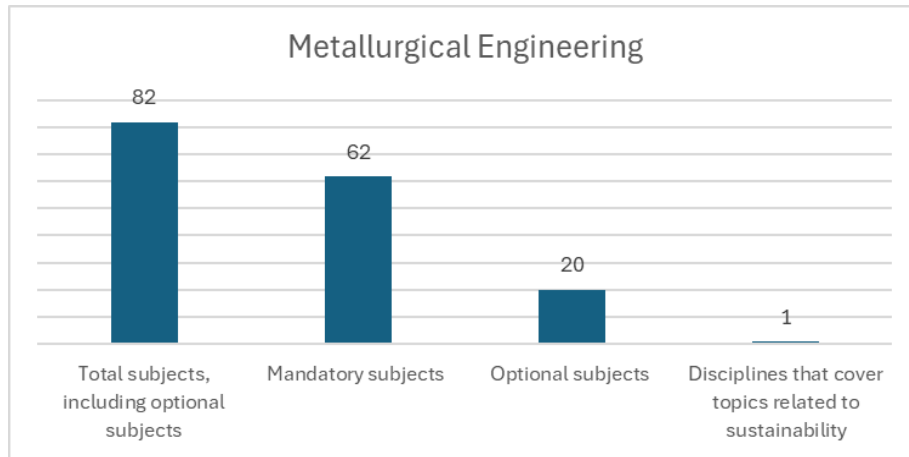
Figure 1: Analysis of the Mechanical Engineering course syllabi



Source: The authors (2024)

Regarding the pedagogical project of the Metallurgical Engineering course, the analysis of the syllabi revealed that out of the 82 courses offered, 62 are mandatory and 20 are elective (Figure 2). The most concerning finding is that only one of these courses addresses sustainability-related topics. These highlights also show a significant gap in the training of future metallurgical engineers regarding the understanding and application of sustainable principles. The metallurgical engineering PPC is in the latest version, updated in 2018.

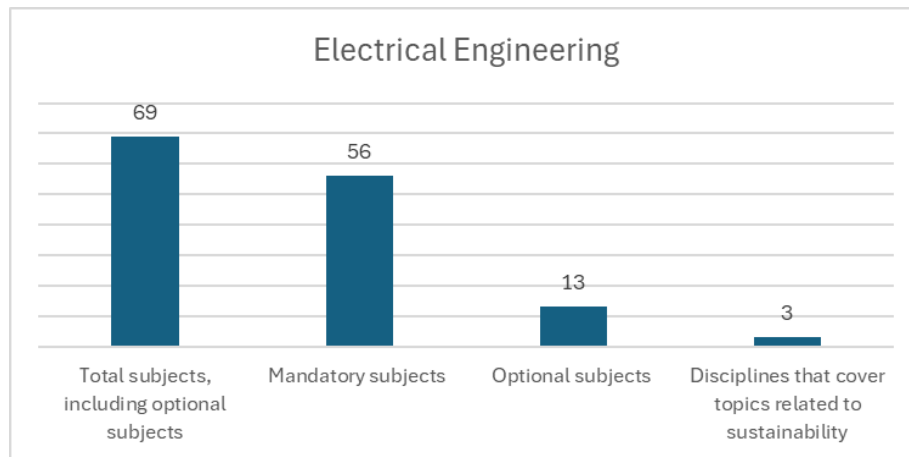
Figure 2: Analysis of Metallurgical Engineering Course Syllabi



Source: The authors (2024)

The review of the Electrical Engineering course subjects showed that out of the 69 available courses, 56 are mandatory and 13 are elective (Figure 3). Only three courses address sustainability issues, indicating a considerable gap in the student's education. In a scenario where sustainability is fundamental, adding more courses focused on sustainability is essential to prepare electrical engineers capable of facing future challenges and contributing to sustainable development. The electrical engineering PPC is the latest, the last update was in 2022.

Figure 3: Analysis of Electrical Engineering Course Syllabi



Source: Author (2024)

Based on the analysis of the PPC and syllabus, it was possible to identify a significant challenge: the lack of a curricular matrix that emphasizes interdisciplinary, including the theme of sustainability. Additionally, the lack of coordination among the various actors in the educational field to promote the incorporation of sustainability was pointed out as a challenge to be overcome. To overcome these obstacles, it is necessary to review institutional guidelines and promote greater

cooperation among the various members of the academic community.

During the interview with the course coordinators, it became clear that sustainability should have a central focus throughout the engineering course, as according to those interviewed, this topic is still very incipient within the course and needs better attention.

The mechanical engineering coordinator highlight that some final projects of the course (known as TCC) address issues related to sustainability and the Sustainable Development Goals (SDGs), even though they do not have a specific course addressing sustainability. Students are integrating the idea of sustainability in all stages of their projects from the beginning. Besides, some professors develop scientific initiation projects with undergraduate students addressing, at least, the environmental dimension. In this sense, there is a research line in the campi dedicated to studies related to bioenergy and the environment.

Although the sustainability theme is mentioned in the analyzed Course Pedagogical Projects (CPP), it is still treated superficially in the three engineering areas. To incorporate sustainability into the engineering curriculum, a cultural shift and clear guidelines from the higher levels of the educational institution are needed.

According to the coordinators, the clear inclusion of sustainability concepts will be done through extension projects to be implemented in the three courses. Furthermore, they are developing a proposal for an integrative project that will be part of the next version of the CPP in 2025. According to the new National Curricular Guidelines (DCN) for engineering courses, an integrative project consists of an educational approach that seeks to integrate the knowledge obtained in various subjects during the course. The aim is to give students the chance to put into practice, in an interdisciplinary way, the theoretical concepts acquired in the classroom to solve real situations. Everyone involved – institution, teachers and students – needs to be engaged in this process. According to those interviewed, previously, engineering courses focused only on central themes, ignoring cross-cutting themes. Respondents believe that institutional policies and broad dissemination are essential to more effectively integrate sustainability into academic curricula.

## 6 Identification of Gaps and Opportunities for Improvement

The inclusion of sustainability in extension and research activities was pointed out as an opportunity to improve students' training and the importance of engineering for the community. The promotion of debates and the sharing of positive experiences are also seen as ways to strengthen the integration of sustainability education. It is essential to update the program contents of engineering courses to highlight the importance of sustainability and provide students with a more comprehensive and conscious education.

The inclusion of sustainability in research and extension activities has been identified as a significant opportunity to enhance student education and emphasize the fundamental role of engineering in society (Hansen, 2019; Silva & Oliveira, 2021). The urgency to revise curricular guidelines is evident in light of the current challenges faced by the environment and society. Sustainability should be included as a central theme in Metallurgical, electrical, and mechanical engineering courses in an interdisciplinary manner, integrating with other fields of knowledge. This integration provides a global perspective, essential for future engineers to create innovative and sustainable solutions (Martins & Souza, 2023). Beyond curriculum updates, it is crucial to foster an academic environment that promotes and values discussions about sustainability. Holding meetings, lectures, and courses dedicated to addressing sustainable practices enables students to share experiences and participate in initiatives promoting sustainable growth. These actions help shape a

more conscious academic mindset dedicated to sustainability values. Reinforcing research and extension activities plays a fundamental role in building student knowledge. Extension projects that engage the local community in sustainable practices not only enrich student education but also highlight the social importance of engineering (Costa et al., 2019). Moreover, research must align with sustainable development goals, promoting innovation and the development of new technologies that reduce environmental impacts (Lima & Ferreira, 2024).

## 7 Conclusion

The field study conducted to examine the inclusion of sustainability in the Engineering program revealed important information about the current state of education in this area. The results showed that despite the growing appreciation of sustainability, its incorporation in the analyzed courses is still limited and incipient. Topics related to sustainability are treated in isolation, without connection between disciplines, which hinders the formation of a comprehensive and interdisciplinary view (following the points presented by Leifler & Dahlin, 2020).

The identified problems include the lack of a curriculum that emphasizes interdisciplinary, making it difficult to effectively promote sustainability in education. The superficiality with which the subject is addressed in the Course Pedagogical Projects (CPP) points to the urgent need for a review of institutional guidelines (Rodríguez-Chueca et al., 2020). However, the study also identified gaps and opportunities for improvement. The inclusion of sustainability in extension and research activities was highlighted as a promising strategy to prepare students and emphasize the importance of engineering for society. The organization of discussions and the exchange of positive experiences can strengthen the integration of sustainability education, creating a more collaborative and committed environment (Desha & Hargroves, 2021).

In summary, the study highlights the need for changes in the Engineering curriculum, suggesting a more integrated and interdisciplinary approach that not only prepares students for current challenges but also equips them to be agents of change in their future careers. The implementation of clear institutional policies and the involvement of all stakeholders are essential for sustainability to become a central element in the training of future engineers.

As a limitation, this study did not interview the professors who are responsible for teaching the mentioned disciplines to verify if they are treating the theme in your courses. "Estado, Mercado e Sociedade", for example, is a course presented in all the engineering PPC, but it involves a large number of concepts and sustainability is only one more of them. Therefore, we could not verify how sustainability is being addressed.

Future studies aim to interview faculty members to investigate how they address sustainability in their courses, focusing on the course "State, Market, and Society." A curricular review that promotes a more integrated and interdisciplinary approach to sustainability is necessary. Additionally, it is essential to review institutional guidelines to ensure a more in-depth and comprehensive approach in the Course Pedagogical Projects, strengthening sustainability education and preparing students to be agents of transformation in their future careers.

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# Incorporating Sustainability in Engineering Education: A Literature Review

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## Abstract

This review article investigates the integration of sustainability into engineering curricula, emphasizing the importance of incorporating sustainable concepts into the training of future engineers. The analysis of academic literature, focusing on references published between 2018 and 2024, also revealed the relevance of older articles found in the bibliographic references. The study evaluates the current state of engineering education, the challenges faced, and the opportunities for integrating sustainable practices. It identifies obstacles such as resistance to change and the disconnect between sustainability and traditional disciplines and underscores the need for active teaching methodologies, such as problem-based learning, to engage students. Examples of successful curricular initiatives are presented, highlighting the urgency of updating study programs. The article concludes that an education focused on sustainability is crucial for preparing students to address the environmental, economic, and social challenges of the 21st century, fostering training that contributes to a more sustainable future.

Keywords: sustainability, university, curriculum, engineering.

## 1 Introduction

The study in question was conducted in Brazil, highlighting the growing importance of sustainability in the field of engineering. In the context of a global demand for more responsible and sustainable practices, there has been a significant push to integrate this theme more effectively into engineering curricula in the country.

With the increasing focus on sustainability in the field of engineering, there has been an initiative to incorporate this topic more efficiently into engineering curricula. Studies have analyzed the current state of sustainability integration in engineering education, along with the obstacles and opportunities for further advancement. (Rosen, 2013) (Byrne et al., 2013)

The study conducted by (Adams et al., 2023) demonstrates the relevance of a unified strategy in education aimed at sustainability, highlighting the urgency of updating university curricula and engaging students in understanding the concepts of sustainability in environmental, economic, and social spheres. Education for sustainable development is considered essential for equipping future professionals and citizens to contribute effectively to a more sustainable tomorrow.

In the article by Castellanos & Queiruga-Dios (2022) "Education for Sustainable Development: An Example of Curricular Inclusion in Environmental Engineering in Colombia," the relevance of sustainability as an essential pillar in environmental engineering education is emphasized. The study highlights the need to integrate the concepts of sustainable development into study programs, aiming to prepare students for contemporary environmental challenges.

An additional study analyzed the opinions of engineering professors regarding the priority sustainability topics to be included in engineering curricula. (Byrne et al., 2013) The results indicate that, despite recognizing the importance of environmental and economic sustainability, these topics were less emphasized by the participants compared to other sources of information. This underscores the urgency of adopting a more comprehensive and strategic approach to integrating sustainable content throughout all engineering courses.

An additional survey was conducted with environmental engineering faculty to analyze the extent to which sustainability has been included in their curricula. (Woodruff, 2006)

A new review analyzed the trends and applications of sustainability in engineering, covering sectors such as energy, infrastructure, and production. (Rosen, 2013) The inclusion of sustainable development and sustainability principles in engineering education has also been a growing area of interest, with calls for greater incorporation of these ideas across all disciplines.

In recent years, sustainability has become a significant topic due to the growing interest in climate change and environmental degradation. To address these global issues, future engineers must be equipped with the appropriate skills and knowledge to create sustainable alternatives. (Arefin et al., 2021).

The increased relevance of sustainability in all sectors of society has created a need to incorporate this subject more effectively into engineering education. Various studies analyze the obstacles and opportunities for a more comprehensive integration of sustainability into engineering programs. (Byrne et al., 2013) (Rosen, 2013).

It is essential to incorporate the concept of sustainability into the education of future engineers to equip them to face current challenges. The importance of this focus is highlighted by ensuring that professionals can propose creative solutions that encompass social, environmental, and economic aspects in an integrated manner (Guerenabarrena-Cortazar et al., 2021).

According to the research conducted by Arefin and collaborators (2021), it is crucial to emphasize the importance of sustainability in the field of engineering right from the beginning of the study, highlighting the urgent need to prepare future professionals for the challenges of the 21st century. According to the researchers, sustainability has gained increasing prominence in recent years due to the growing concern about climate change and environmental degradation. To address these global challenges, the next generation of engineers must be adequately trained with the fundamental knowledge and skills to develop sustainable solutions.

A study conducted in 2013 analyzed the views of engineering professors on the key sustainability concepts that should be included in engineering curricula. According to Byrne et al. (2013), the results indicate that, despite the recognition of the importance of environmental and economic sustainability, these topics were less emphasized by the participants compared to other studies. This underscores the urgency of a more comprehensive and strategic approach to integrating sustainability content into all engineering programs.

A new survey was conducted with environmental engineering faculty to analyze how sustainability has been integrated into curricula (Woodruff, 2006). Additionally, an analysis was conducted on the directions and uses of sustainability in engineering, covering sectors such as energy, infrastructure construction, and goods production. The introduction of sustainability and sustainable development concepts into engineering education has become increasingly important, with calls for greater incorporation of these concepts across all disciplines of the course.

## 2 Challenges and Barriers to Sustainability Integration

The importance of engineers in addressing global sustainability issues has been widely accepted (Crofton, 2000). Integrating sustainability into engineering education is crucial to ensure that future engineers have the knowledge, skills, and methods necessary to contribute effectively to sustainable growth (Crofton, 2000) (Rosen, 2013).

Sustainable engineering involves a broad range of factors to be considered, such as environmental, economic, and social issues (Byrne et al., 2013) (Rosen, 2013). Previous studies emphasize the importance of engineering programs including sustainability-related content and skill development opportunities throughout the course, through the introduction of subjects and practical experiences that address topics such as energy efficiency, renewable energy sources, sustainable materials, and life-cycle analysis (Yosie, 2014).

Despite the growing recognition of the relevance of sustainability in engineering education, various obstacles have hindered the effective incorporation of sustainability-related topics and activities into engineering educational programs (Byrne et al., 2013) (Crofton, 2000).

According to the study by (Arefin et al., 2021), the importance of sustainability lies in equipping future engineers to tackle current challenges, which are associated with climate change and environmental degradation.

They argue that future engineers need to have the knowledge and skills to develop solutions that meet current demands without compromising the ability of future generations to meet their own needs. According to the researchers, sustainability is believed to be more than just an abstract idea; it is fundamental to the future of engineering. Therefore, engineers play a crucial role in creating technological innovations, infrastructure, and systems aimed at a more sustainable and resilient future.

## 3 Opportunities for Integrating Sustainability in Engineering Education

Despite the challenges, there are several opportunities to efficiently integrate sustainability into engineering education. Recent research highlights the increasing demand from both companies and students for knowledge, skills, and competencies related to sustainability (Yosie, 2014).

This need, combined with the advancement of consistent knowledge and sustainability guidelines, provides a robust foundation for enhancing sustainability content and experiences within engineering programs (Yosie, 2014).

Specific ways to include sustainability in engineering education are: establishing new courses or teaching units that address sustainability issues, such as renewable energy sources, sustainable materials, and environmental impact assessment; incorporating case studies, projects, and practical activities related to sustainability into existing courses; and creating interdisciplinary programs or specializations that connect engineering, environmental sciences, and other sustainability-related fields (Crofton, 2000) (Yosie, 2014).

By proactively addressing obstacles and exploring opportunities to promote the integration of sustainability, engineering programs have the potential to train professionals who can become effective leaders and problem-solvers in addressing the various sustainability challenges that the world faces today and will face in the future.

## 4 Methods

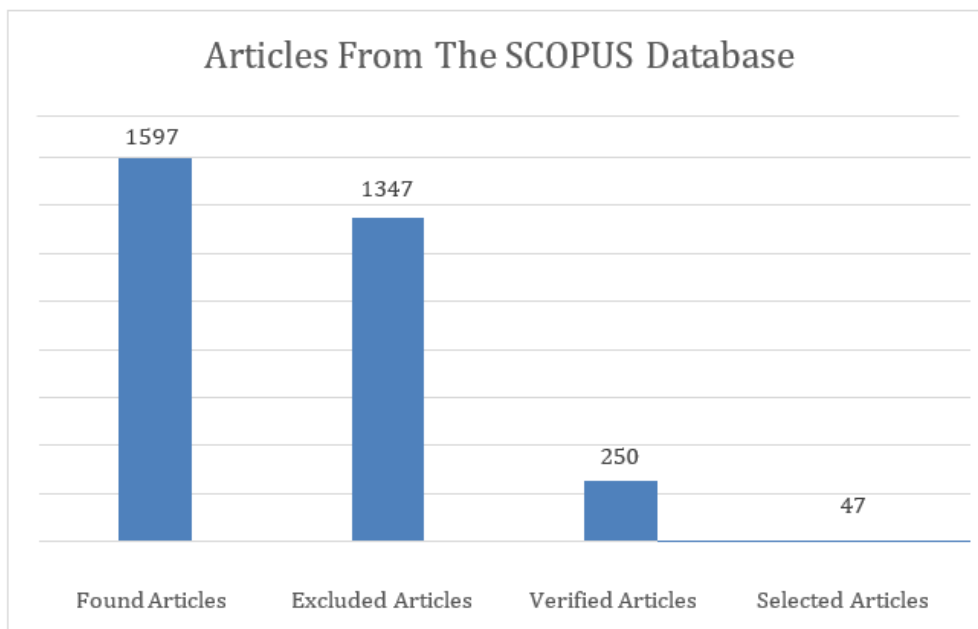
To conduct this literature review, the author carried out a thorough search on the Scopus

platform, using a specific set of keywords, namely *sustainability*, *university*, *curriculum*, and *engineering*, to locate articles related to the integration of sustainability into engineering curricula. Initially, the search resulted in a total of 1597 records. This substantial number of results highlighted the importance of the topic but also emphasized the need to refine the search to ensure that only the most relevant articles were considered. To achieve this, the author limited the search to the years 2018 to 2024, thus obtaining 250 articles deemed truly suitable for the literature review. It is worth noting that, during the article selection process, it was specified that all should be in English. This time frame was chosen to reduce the number of records, focusing on the most recent and relevant studies that represent current practices and trends in integrating sustainability into engineering curricula.

Although the search was restricted to the period from 2018 to 2024, other relevant articles were found, even those from years before the specified range. The author also established the criterion that the articles should be available in English. This choice was made to refine the search, as English is widely recognized as the primary language of international academic literature. Finally, to ensure the quality and relevance of the selected articles, the author filtered the results to include only articles published in specialized journals. This final step was essential to further refine the search and ensure that the analyzed documents were of high quality and peer-reviewed.

This organized and refined research technique allowed the researcher to gather a selection of relevant and high-quality articles for the literature review, thus establishing a solid foundation for exclusively analyzing the integration of sustainability into engineering curricula.

Figure 1: Number of articles found and selected from the SCOPUS database.



Source: The authors (2024)

## 5 Problem-Based Learning

Problem-based learning emerges as a promising educational strategy for integrating sustainability into engineering education. This approach focuses on solving realistic and complex challenges, motivating students to view issues broadly and apply their knowledge and skills in an integrated manner (Azapagic et al., 2005) (Yosie, 2014) (Guerenabarrena-Cortazar et al., 2021).

Through problem-solving approaches, engineering students can engage in projects that address sustainability issues, such as designing renewable energy systems, improving energy efficiency in buildings, or minimizing environmental impact in manufacturing processes (Guerra, 2017). This educational methodology allows students to develop essential skills such as critical thinking, problem-solving, teamwork, and communication—skills crucial for future engineers to contribute meaningfully to the transition toward more sustainable societies (Thürer et al., 2018) (Carvalho et al., 2018) (Inéia et al., 2023) (Juliano et al., 2017).

## 6 Engineering and Its Interface with Society

A crucial point discussed in various works is the need to foster a greater connection between engineering education and society. This includes not only incorporating socio-environmental topics into the curriculum but also establishing partnerships with the community, non-governmental organizations, and other stakeholders, enabling students to apply their knowledge to projects aimed at the collective good (Carvalho et al., 2018) (Juliano et al., 2017).

The way this is approached allows engineering students to gain a deeper understanding of the social and environmental consequences of their professional activities, thus promoting a broader and more conscious perspective on their careers. Additionally, engagement with the community can motivate students to adopt more ethical and committed attitudes toward sustainable progress.

## 7 Stakeholder Engagement

Students pursuing engineering have demonstrated willingness and active participation in discussing sustainability-related topics during their problem-based classes, indicating that this educational method can be effective in enhancing their skills in this field (Guerra, 2017).

At the same time, engineering colleges have been committed to including sustainability in their academic programs with the aim of preparing students with a broad and committed perspective on their future profession (Carvalho et al., 2018) (Inéia et al., 2023).

When facing real-world challenges related to sustainability, engineering students have the opportunity to deepen their understanding of the problems and responsibilities involved, as well as to seek innovative ways to find solutions that consider environmental, social, and economic aspects (Hasna, 2010).

This teaching approach not only helps students better retain the content but also aids in the development of important competencies such as critical analysis, collaboration, and communication, which are essential for sustainable engineering (Yosie, 2014).

## 8 Challenges and Barriers to Incorporating Sustainability in Engineering Education

The lack of agreement on which sustainability topics and skills should be emphasized in engineering education is identified as one of the major obstacles (Byrne et al., 2013).

Additionally, the classical engineering education often places more importance on technical and disciplinary aspects rather than comprehensively considering sustainability, which makes it difficult to include sustainability-focused content in the curriculum (Crofton, 2000).

Furthermore, the certification criteria and the parameters of existing engineering education programs may not adequately highlight the relevance of sustainability, resulting in limited incentives for institutions to prioritize its inclusion in the curriculum (Yosie, 2014).

## 9 Strategies and Best Practices for Incorporating Sustainability in Engineering Education

To address these challenges, previous studies have highlighted several strategies and best practices for efficiently integrating sustainability into engineering education: First, it is essential to establish a clear and shared understanding of the specific sustainability-related knowledge, skills, and competencies that should be prioritized in engineering education (Byrne et al., 2013). This can be achieved through collaboration among engineering faculty, industry partners, and other stakeholders to define the core sustainability learning objectives for engineering graduates.

Next, it is crucial for educational organizations to consider adopting a systems-level approach when designing the curriculum, incorporating sustainability-related content and learning experiences across different courses and program areas, rather than addressing them in isolation (Wilson, 2019).

Furthermore, it is possible to engage students in real-world sustainability issues and foster their critical thinking and problem-solving skills through the use of active learning methodologies, such as project-based learning and service learning. These approaches, according to Chandu & Kancharla (2012) and Hasna (2010), have proven effective for this purpose.

Lastly, it is essential to promote strong alliances and cooperation between engineering projects, companies, and the local community, ensuring that sustainability education aligns with the demands and goals of society as a whole.

## 10 Gaps identified

The need to promote sustainability in engineering is fundamental today. However, the inclusion of this topic in engineering courses still presents obstacles, as mentioned in the study "(Arefin et al., 2021) Incorporating Sustainability in Engineering Curriculum: A Study of Australian Universities." One of the main difficulties identified is the lack of connection between sustainability and conventional disciplines.

Many engineering courses still prioritize technical and specific understanding, which makes it difficult to dedicate the necessary time and resources to address sustainability topics (Crofton, 2000).

Additionally, the divergence of opinions regarding the specific sustainability skills that should be highlighted in engineering education represents a challenge in creating a unified and comprehensive strategy (Thürer et al., 2018).

Another issue highlighted is the urgency to conduct more practical studies to analyze the effectiveness of different teaching methodologies in fostering students' sustainability-focused knowledge, skills, and attitudes.

An additional obstacle is the lack of agreement on which specific sustainability skills should receive the most priority in engineering education. Scholars have emphasized the need for more research to understand the views, values, and knowledge of both students and professors regarding sustainability (Thürer et al., 2018).

It is also important to analyze the impact of key stakeholders, such as accreditation bodies, industry partners, and the community, on the integration of sustainability in engineering courses (Thürer et al., 2018).

Broadly, the literature highlights the importance of following an organized, holistic, and participatory strategy to integrate sustainability into all engineering disciplines, rather than relying on isolated actions.

## 11 Conclusion

The inclusion of sustainability in engineering education programs is not only urgent but essential, given the current environmental, social, and economic challenges the world faces. The growing climate crisis, depletion of natural resources, and the need for a circular economy make training engineers with sustainability skills a global priority. Without this approach, progress toward a more sustainable future will be significantly hindered.

This article emphasizes the importance of adopting innovative teaching methods, such as problem-based learning and active techniques, which not only engage students but also empower them to apply sustainable concepts in practice. The literature review suggests that, despite challenges such as resistance to change and lack of resources, efforts to integrate sustainability into engineering curricula are showing positive results and should be intensified. Higher education institutions have a responsibility to continuously refine their programs by incorporating sustainability as a central element of engineering education, ensuring that future professionals are equipped to address the complex challenges of the 21st century in an ethical, innovative, and sustainable manner.

Furthermore, collaboration among educators, students, and industry will be crucial to transforming engineering education and ensuring that graduates are prepared to develop technological solutions that contribute to a more resilient and sustainable future. Future studies should explore the effectiveness of different teaching methods in sustainability within engineering programs, focusing on how these approaches impact students' understanding and practical application of the concepts.

Thus, the relevance of sustainability in engineering education goes beyond a mere trend; it is an urgent necessity to ensure the well-being of future generations and the preservation of the planet.

## 12 Final Considerations

Here are the implications of the conclusion translated into English:

- a) **Global Priority for Sustainability Training:** The conclusion highlights that integrating sustainability into engineering education programs is a global priority. This implies that educational institutions must quickly recognize and act to incorporate sustainability skills into their curricula to prepare future engineers. Without this focus, progress toward a more sustainable future will be hindered, potentially leaving unresolved environmental and social challenges.

- b) Importance of Innovative Teaching Methods:** Adopting innovative teaching methods, such as problem-based learning and active techniques, is crucial for engaging students and empowering them to apply sustainability concepts in practice. This suggests that universities should invest in pedagogical methods that promote the practical and critical application of sustainability concepts, rather than relying on traditional methods that may not adequately prepare students for real-world challenges.
- c) Responsibility of Higher Education Institutions:** Higher education institutions have the responsibility to continuously refine their programs by making sustainability a central element of engineering education. This implies an urgent need for curriculum review and updates to integrate sustainability comprehensively and continuously, ensuring that future professionals are well-equipped to address 21st-century challenges ethically and innovatively.
- d) Need for Multidisciplinary Collaboration:** Collaboration among educators, students, and industry is essential to transform engineering education and ensure that graduates are prepared to develop sustainable technological solutions. This suggests that coordinated efforts and partnerships among different stakeholders are necessary to ensure that engineering education evolves to meet the demands of a sustainable future.
- e) Requirement for Future Research:** Future studies should explore the effectiveness of different teaching methods in sustainability, focusing on how these approaches impact students' understanding and practical application of concepts. This indicates a need for further research to evaluate and improve pedagogical practices related to sustainability, ensuring that the teaching methods used are the most effective in preparing engineers for real-world challenges.
- f) The urgency of Sustainability:** The conclusion underscores that sustainability is not a passing trend but an urgent necessity to ensure the well-being of future generations and the preservation of the planet. This implies that immediate and effective actions are required to incorporate sustainability into engineering education and to address environmental and social issues proactively.

These implications suggest a critical need for structural and methodological changes in engineering education to ensure that graduates are prepared to contribute to a more sustainable and resilient future.

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# Supply chain management of photovoltaic modules: state of the art through prisma

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## Abstract

This study aimed to analyze the state of the art of the supply chain of photovoltaic modules in the context of the energy transition, regarding renewable energies, Addressing Disposal and the recycling of photovoltaic modules that present environmental challenges and opportunities. A concise and rigorous literature review was developed, using the PRISMA method, regarding the supply chain of photovoltaic modules, providing clear conclusions and reliable, providing the opportunity to critically evaluate and comprehensively gather the results identified in the literature of various published articles. Initially, an analysis of publications from the last 5 years was presented, where an increase of 70% of publications was observed in 2021 compared to previous years. Then, the publications were analyzed by country, with Italy, the United States of America and Australia being the countries with the highest publications in the analyzed period. Subsequently, a critical analysis of the publications with the highest citations was developed, in order to identify an important gap that needs to be filled and to verify uncertainties about future compliance issues, due to the absence of specialized regulation on waste produced in the supply chain of photovoltaic panels. Finally, the importance of reverse logistics in the photovoltaic value chain was discussed, regarding the recycling of solar panels and the reuse of their components. As can be seen in the literature review carried out, the creation of regulatory measures in waste produced in the supply chain of photovoltaic panels is important for the development of new methods, which can later be applied in the reverse logistics of the solar panel supply chain.

**Keywords:** Supply chain management; PRISM; Photovoltaic; Systematic Review of the Literature.

## 1 Introduction

There are several sources of renewable energy, each with its own characteristics and way of obtaining it, presenting a series of significant benefits. However, in this study, photovoltaic energy will be the object of analysis, considered one of the most attractive renewable energy vectors for the generation of electricity in a clean way, bringing benefits to the reduction of global warming.

However, the supply chain of photovoltaic panels used on a large scale has been an open problem, because considering the average lifespan of these panels, between 25 and 30 years, it is estimated that, to date, there is a significant number of photovoltaic panels that are about to reach their end of life,

giving rise to a high amount of waste. It is expected that, by 2050, with the continued high rate of implementation of photovoltaic panels, about 60-70 million tons of photovoltaic panel waste will be produced worldwide. This waste is being sent to landfill and/or incineration, with no possibility of recycling, bringing up a point of attention, since the panels may contain high value-added materials, such as silver, silicon and copper, which were considered critical by the European Commission, due to the forecast of their scarcity (Gahlot, et al, 2022). In the coming years, large quantities of this equipment will be discarded (Machado, 2017), and it is extremely important that the final destination occurs in an environmentally correct manner, preventing the disposal from being inappropriately disposed of in landfills (Marsh, 2018). In addition, the recycling of materials also makes it possible to reduce the consumption of energy generation for the creation of the same components, compared to the creation of their raw material (Maia, et al, 2022). However, it is still necessary to implement and adapt specialized policies, which thus characterizes a challenge regarding the final destination of photovoltaic solar panels. (Cruz, et al, 2020).

The systematic review of the proposed literature on risk management in the supply chain of photovoltaic modules is promising to identify scientific opportunities, considering the ESG dimensions directed to the formulation of policies and regulations that promote the reuse of components at the end of their useful life, always considering the principle of circular economy and avoiding the accumulation of the disposal of these components in landfills.

In this article, an analysis of the critical points and relevant solutions related to the disposal and recycling of photovoltaic panels and their components through the supply chain of photovoltaic modules in the world scenario linked to the energy transition from the perspective of ESG will be presented.

## 2 Materials and Methods

In this study on Risk Management in the Supply Chain of photovoltaic modules, the approach is through a systematic analysis of the literature through the (*Preferred Reporting Items for Systematic Reviews and Meta-Analyses*) - *PRISMA*. This comprehensive analysis helps to identify the main studies related to the topic, focusing on strategies to mitigate the negative impacts of the disposal and recycling of these modules, which present environmental challenges and opportunities.

The guidelines of the *PRISMA method* consist of a checklist with 27 items duly explained and exemplified, in addition to a flow diagram divided into four steps (Liberati et al., 2009). According to the instructions of this method, the research was carried out in four distinct phases: Identification, Screening, Eligibility and Inclusion.

During the Identification phase, the themes and databases to be studied are selected, allowing the inclusion of other databases to materialize other documents. During the Screening phase, the inclusion and exclusion criteria are detailed. The reading of the articles selected in the previous stage and their exclusion must be justified and accompanied by an explanation in the Eligibility stage. Finally, only documents that meet the criteria of the previous step are added to the Inclusion step.

### 2.1 Qualitative analysis using the *PRISMA method*

The analysis performed in this study is based on documents found in the *Scopus* database using the following *string*: *TITLE-ABS-KEY* ("photovoltaic panel\*") AND ("supply chain" OR "supply chain management" OR "supply chain risk management" OR "supply chain resilience"). *Scopus* was chosen because it is a relevant database that offers consistency, standardization and reliability. It considered all types of documents in English between 2015 and April 2024; Based on the *string* used, 32 documents were found. Selecting a filter to limit only search-type and review-type articles reduced the results to

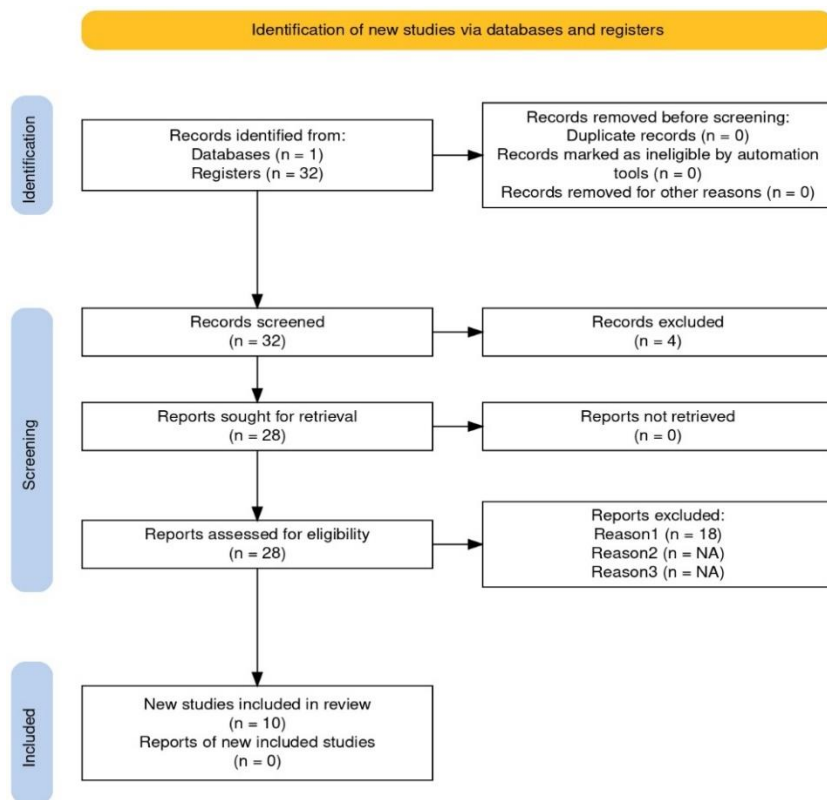
28 articles and 4 exclusions. Thus, the data were later exported for application in the elaboration of graphs and tables presented in this work.

## 2.2 Qualitative analysis using the *PRISMA method*

Using the selected documents, whose data were compiled in a table, in order to identify the most relevant research priorities regarding the current state of PV module supply chain management and its contribution to the literature.

Figure 1 illustrates the PRISMA flow diagram, as mentioned earlier, representing the phased process. In the "Identification" stage, the results of the search made in the Scopus database are displayed, which revealed 32 documents. During the "Screening" stage, exclusion criteria were applied to choose the documents to be analyzed in this study. One editorial, one review of the conference, one conference article, and one book chapter were excluded. After selecting the most relevant articles, 28 of them met the inclusion requirements for the review.

In the "Eligibility" phase, both the title and the abstract were thoroughly evaluated to ensure the relevance of the researched topic; In addition, only articles with citations were taken into consideration. Thus, 10 articles met the eligibility criteria and finally, in the "Inclusion" phase, the number of documents included in the meta-analysis was presented.



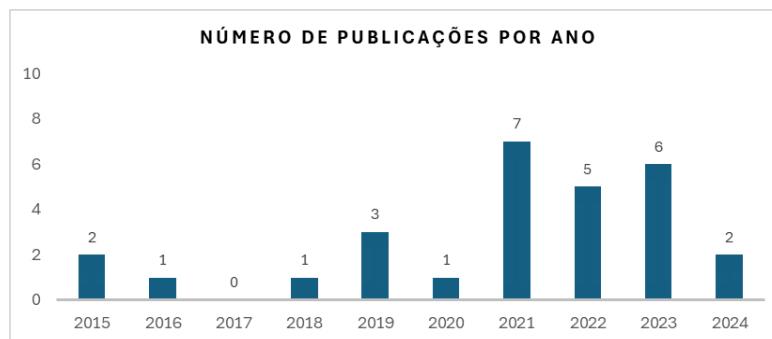
**Figure 1** - PRISMA flowchart for systematic review applying the SCOPUS database

### 3 Results and discussions

As a result of the *PRISMA analysis*, several articles were published by countries located in the European Union (EU), where pioneering companies in the segment of environmentally correct final disposal of photovoltaic panels are located, corroborating the theme effectively. The topic is addressed on different fronts, from the manufacture of the raw material, to residential or industrial application and at the end of its useful life: disposal, in landfill or in a sustainable way; For the same purpose, there is the reuse of secondary raw materials to manufacture new products for resale to the public. The approach to reverse logistics management for photovoltaic panels when they reach their end of life is still little mentioned in detail in articles and research, so this research brings together the literature that brings to light the supply chain process for photovoltaic modules by compiling the articles located in the Scopus database. However, it is soon noted that there is still a need for investment in research and new works in this segment, because in the following topics it was possible to observe that there are few countries and articles that have addressed this theme.

#### 3.1 Analysis of publications from the last five years

Analyzing all the years where articles published on this topic are found, it is observed that the searches and articles began in 2015, but the years 2021 and 2023 were the ones that stood out the most in terms of publications, as shown in Figure 2. There is a highlight for the year 2021, with an increase of 70% in publications on the subject, compared to the sum of the total publications in previous years, since 2015.

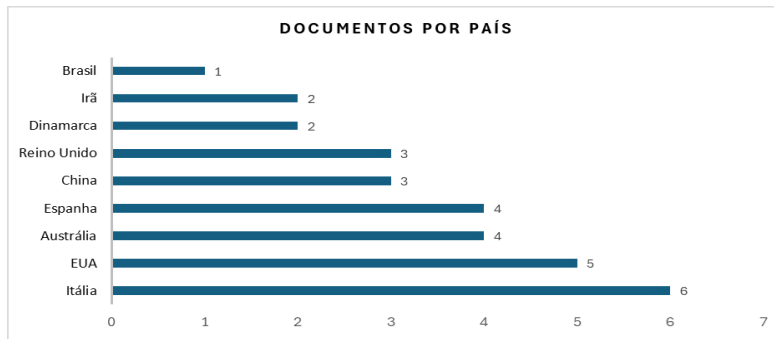


**Figure 2** - Distribution of selected articles by year of publication

It is believed that this fact was due to the challenges arising from COVID-19, which brought risks to the production chain, which was highly affected during the pandemic, as consumers chose to buy survival products, such as: food, medicines, face shields, etc. As global logistics was affected by the lack of containers and capacity on vessels, delays in ship calls, congestion in ports and the increase in the price of Chinese sea freight, there was a lack of raw materials for the manufacture of solar modules in this period. At that time, raw materials were imported from China and even countries like Brazil made use of Chinese photovoltaic modules. It should also be noted that for the year 2024, only the documents published up to the date of the execution of this work (April 2024) were considered.

### 3.2 Analysis of publications by geographical context

The countries that produced the most articles on the topic analyzed were Italy, the United States of America and Australia, which published 6, 5 and 4 articles, respectively. The publications extended to most European Union countries and China, corroborated in the analysis.



**Figure 3** - Distribution of selected articles by geographic context

It is important to note in Figure 3 the divergent situation among the BRICS countries. Unlike China, India, and Brazil, no article on this topic was published by South Africa and Russia between 2015 and 2024, considering the filters applied; a possible explanation for China's role being highlighted may be the size of the national population and the search for alternatives to reduce atmospheric emissions, mainly caused by the transport sector.



**Figure 4** - Distribution of the selected articles by country

Based on Figure 4, it is observed that Brazil has a low rate of research published at a global level on the subject, despite the country being highlighted by the generation of photovoltaic solar energy and being in the top 10 of the world ranking as the largest producer of solar energy. However, comparing the number of publications in Brazil with Italy, it is observed that the European country published 83% more for the same period analyzed (2015 to 2024).

### 3.3 Analysis of study publications from the last five years

Table 1 presents the summary with the characteristics of the research bases used by several authors, methods applied in supply chain management and the main results for each study carried out.

It starts from the study carried out by Ansanelli, et al, 2021, which addressed the Life Cycle Assessment (LCA) of a photovoltaic panel recycling process, to evaluate the environmental performance of the recovery of secondary raw materials. The objective of this research was to provide an overview of the environmental loads and benefits, identify critical points related to the recycling of C-Si photovoltaic panels, which is the most common model found in the international market, verify the destination of end-of-life (EoL) panels and evaluate the sustainability of the state-of-the-art treatment offered in the recycling of this type of panels. This study focused on the recovery of secondary materials from photovoltaic panels to determine the environmental advantages of the photovoltaic recovery system, despite the energy loads generated by the recycling treatment. One of the challenges in the recycling process then becomes the need to improve critical steps and reduce the impacts of transport, as well as solutions that involve improving energy consumption and the adoption of renewable alternatives, the efficient use of chemicals and equipment in the solar panel supply chain.

Item	Title [Reference]	Supply chain stage	Disposal Methodology	Conclusions
1	1) Ansanelli, G., Fiorentino, G., Tammaro, M., Zucaro, A. (2021). A Life Cycle Assessment of a recovery process from End-of-Life Photovoltaic Panels	The transportation of PV panels from the collection points to the recovery line and the fraction of PV glass from the recovery line to the glass reuse line.	Recover secondary raw materials such as aluminum, copper, silver, silicon, and glass from the panels. Challenges in the recycling process include the need to improve critical steps and reduce transportation impacts.	The study evaluated the environmental impacts of the photovoltaic panel recycling process, highlighting the importance of transportation in determining the environmental performance of the system.
2	2) Corcelli, F., Ripa, M., Leccisi, E., Cigolotti, V., Fiandra, V., Graditi, G., Sannino, L., Tammaro, M., Ulgiati, S. (2018). Sustainable urban electricity supply chain – Indicators of material recovery and energy savings from crystalline silicon photovoltaic panels end-of-life	End-of-life of crystalline silicon PV panels in the urban electricity supply chain.	The recovered materials, such as aluminum, glass, copper, and metals, are sent for recycling to obtain secondary raw materials, while the inert fraction of the ash is used in cement plants.	The recovery of aluminum and silicon from photovoltaic waste panels has significantly reduced the need for raw material extraction, reducing manufacturing costs and improving end-of-life management.
3	3) Gautam, A., Shankar, R., Vrat, P (2021). End-of-life solar photovoltaic e-waste assessment in India: a step towards a circular economy.	Projection of a reverse supply chain based on the circular economy.	A prediction model was used that projected the amount of waste generated by end-of-life photovoltaic solar panels and their system balance, using the Weibull reliability function for panel failures.	Maximize resource efficiency by creating facilities for a circular economy-based supply chain to address the massive e-waste generated by solar PV panels in India.
4	4) Besiou, M., Van Wassenhove, L.N. (2016). Closed-Loop Supply Chains for Photovoltaic Panels: A Case-Based Approach.	Production, collection, supply of photovoltaic energy and recovery of photovoltaic panels along the closed-loop supply chain.	Challenges include a trade-off between recyclability and durability, difficulty estimating future waste streams, and concerns about low-quality recycled materials affecting electricity generation.	There is a lack of expertise in closed-loop PV supply chains, and voluntary initiatives before regulations have added complexity to the research.
5	5) Lapko, Y., Trianni, A., Nuur, C., Masi, D. (2019). In Pursuit of Closed-Loop Supply Chains for Critical Materials: An Exploratory Study in the Green Energy Sector.	Closed-loop supply chain for critical raw materials in the green energy sector, specifically in panels and wind turbine technologies.	The panels must be collected and dismantled in a proper manner to separate the constituent and recycled materials to be introduced into the supply chain. In addition, hazardous waste must be treated in accordance with environmental regulations.	The study pointed to the lack of dialogue between the different actors in the supply chain and incentives, hindering the effective implementation of CLSC. This is one of the challenges related to the development of CLSC for critical materials in the green energy sector.

Item	Title [Reference]	Supply chain stage	Disposal Methodology	Conclusions
6	6) Mahmoudi, Sajjada; Huda, Nazmula	"Macroscopic" phase of the supply chain, which involves the management of end-of-life (EOL) photovoltaic waste at the product and component level.	The end-of-life (EOL) photovoltaic panel disposal methodology involves several scenarios, such as reuse, recycling, and recovery of materials and substances, which can be evaluated based on ISO 14040 and 14044 standards.	Not all recovered materials are 100% recycled. There is also the process of recycling and recovery of discarded photovoltaic panels through mechanical disassembly, thermal and chemical separation, which can generate and release toxic substances into the environment.
7	7) Kolahchian Tabrizi, M., Famiglietti, J., Bonalumi, D Campanari, S. (2023). The Carbon Footprint of Hydrogen Produced with State-of-the-Art Photovoltaic Electricity Using Life-Cycle Assessment Methodology	Closed-loop supply chain that incorporates informal recyclers (IRS).	Most of the GHG emissions are related to the production of energy through the photovoltaic system. Therefore, there is a need to use renewable electricity during the production stages of the modules.	There is no description or approach for the disposal of the modules. Only the 30-year lifespan for photovoltaic generation systems is mentioned.
8	8) Salim, H.K., Stewart, R.A., Sahin, O., Dudley, M. (2021). Dynamic modelling of Australian rooftop solar photovoltaic product stewardship transition.	End-of-life (EoL) management system for rooftop solar photovoltaic (PV) panels in the PV supply chain.	Four plausible flows are pointed out: disposal in landfills, storage, repair and recycling. However, consumers or installers are more attracted to the landfill disposal option.	Shared responsibility has balanced outcomes across the board, including collection and retrieval outcomes. Despite being the best-performing scenario, the disruptive change trajectory is expected to cause a 7.3% drop in PV adoption by 2050.
9	9) Iakovou, E., Pistikopoulos, E.N., Walzberg, J., Iseri, F., Iseri, H., Chrisandina, N.J., Vedant, S., (2024) Next-generation reverse logistics networks of photovoltaic recycling: Perspectives and challenges.	Supply chain reverse logistics systems for end-of-life (EoL) photovoltaic panels.	Recycling is sometimes considered unattractive (expensive) compared to alternatives such as landfilling. Within the reverse logistics network, three recycling processes in particular have shown potential: FRELP, ASU and the hybrid.	The low level of recycling adoption causes delays in market readiness and further increases the associated costs.
10	10) Hidalgo-Carvajal, D., Carrasco-Gallego, R. (2022). Preparing for future e-waste from photovoltaic modules: a circular economy approach	Closed-loop supply chain that incorporates informal recyclers (IRS) to enhance the management of waste electrical and electronic equipment.	Most recycling efforts are focused on the c-Si type, relying on three types of recycling: mechanical, thermal and chemical.	In essence, the study concluded that integrating informal recyclers into the supply chain and adopting sustainable practices are crucial for effective WEEE management and environmental sustainability.

**Table 1 - Main characteristics and results of the selected articles**

While Mahmoudi, et al, 2021, brought to light the study and in-depth exploration of current efforts on PV waste management that revealed a lack of a holistic management framework that addresses the PV waste stream in terms of product and component, material and substances, the results showed that PV recycled materials have the potential to be employed in the same or other industries, such as the construction industry, the ceramic tiles industry, among others.

The research indicated that the sustainability of photovoltaic panels should be divided into three main levels: product and component, material and substances.

A more recent paper published by Iakovou, et al, 2024, conducted in the United States indicated that a critical factor impacting the cost of PV system recycling is volume; of PV modules that are nearing their end of life and due to the low level of recycling adoption, delays occur in market readiness, further increasing the costs associated with environmentally friendly disposal. Collaborative efforts between governments and regulation with the application of incentives for the repair, reuse and recycling of photovoltaic waste are some of the challenges to be overcome in the search for the correct segment of the supply chain flow.

It is observed that there is indeed an important gap that needs to be filled and that there are also uncertainties about future compliance issues due to the absence of specialized waste regulation. The global lack of extended responsibility regulations from the producer of raw materials, manufacturers of the panels to the user who ultimately produces the photovoltaic waste at the end of the useful life of the modules, is a challenge to be overcome. If there is no global standard, the trend that should continue to be implemented is an inadequate treatment strategy, including a weak monitoring system, low rate of valuation of reverse logistics networks and superficial or poorly comprehensive logistics networks. All

these weaknesses are a serious challenge and can cause major losses, such as resource depletion, environmental burdens and risks to the health of animals and humans.

## 4 Reverse logistics in the photovoltaic value chain

To date, no regulation or legislation applied at the global level has been identified that presents the guidelines for the final disposal of photovoltaic waste. Some countries seek regulation, for example, in the United States, the Federal Resource Conservation and Recovery Act, the standardization of the disposal of hazardous photovoltaic waste at the end of its useful life. It is observed that in China, as far as we know, there is no regulation in this regard for the photovoltaic industry. (Kaczmar et al. 2008).

Although Brazil is one of the most abundant countries in energy generation from renewable sources and has shown vast growth in electricity generation through solar sources over the years, there is also no regulation that specifically deals with the destination of photovoltaic panels after the end of their useful life.

### 4.1 Recycling of solar panels

When we approach the entire life cycle of energy generation from solar photovoltaic sources, we are faced with a large flow of materials and implemented technologies that generate a volume of waste that cannot be ignored. In view of this, some solutions are emerging to minimize the effects of decommissioning panels at the end of their useful life. In this sense, initiatives are being implemented mainly in Europe, where Directive 2002/96/EC was established and which has been under review over the years, as observed in the new adaptation carried out in 2024. As a result of the Directive, in 2007 there was the creation of the PV CYCLE (<https://pvcycle.org/>) association, which collects and recycles Electrical and Electronic Equipment – EEE, including photovoltaic panels and inverters; and as far as we know, it is the first existing collective scheme funded. (Besiou, 2012).

There are companies that stand out in studies and initiatives for recycling to occur; Two of them are mentioned in several articles.

One of the companies mentioned is First Solar, a factory that designs its panels in frameless glass in order to facilitate recycling after its life cycle. (Fthenakis et al., 2006). For this process to be carried out, the company has developed hydrometallurgical processes based on leaching, ion exchange separation, precipitation and electrolytics for cadmium and tellurium recovery of CdTe-type panels. (Corcelli et al., 2018). However, it and other companies point to challenges such as stricter public policies, the absence of recycling infrastructure, in addition to the current small volume of end-of-life photovoltaic modules as obstacles to the development of the supply chain of materials from solar energy generation. (First Solar, 2023).

### 4.2 Reuse of solar panel components

One of the means of reusing materials after the recycling process is their recovery for use in the manufacture of new products, for example, First Solar recovers glass for use in the manufacturing process of new glass packaging; In addition, it uses the metallic material that is part of the support structure of the modules for the creation of new aluminum products. The laminated material is used in the creation of new rubber products. (First Solar, 2023).

Another solution applied is the use of photovoltaic module components for the manufacture of new panels, avoiding production from virgin materials. However, reuse implies applying several

treatment processes: thermal, mechanical and chemical, which may not be advantageous due to the use of high loads of electrical energy necessary in the heat treatment stage of components such as copper, aluminum and silver.

## 5 Conclusion

It is observed that the generation of electricity by photovoltaic technology produces a significant volume of waste at the end of the useful life of the modules, which cannot be ignored. Studies and research on recycling and reuse of materials are needed, however, few countries have implemented guidelines for waste management along the supply chain of photovoltaic modules and there is still no effective global legislation for the proper disposal of this waste.

This article highlighted the need for a more in-depth study of the PV module supply chain, the implementation of infrastructure, the introduction of regulatory measures with relevant public policies, and new research for the application of reverse logistics. This will allow the reduction of costs in the process of recycling or reusing waste over the years. Contributing to the conservation of natural resources, because without these changes, the environment will continue to be harmed, there is also the risk of depletion of the raw materials necessary for the manufacture of new solar panels, compromising the necessary energy transition. For future work, studying the existing legislation is essential to understand and propose improvements in the obligations of solar panel manufacturers and industries that produce raw materials for photovoltaic module components. Additionally, it is important to consider the circular economy, which can add value by including informal recyclers, contributing to the closed-loop supply chain, and aligning with ESG principles.

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# Comparative Analysis on the Energy Markets of Portugal and Brazil

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## Abstract

Energy markets have a significant impact on a country's energy transition, as it is understood that in liberalized markets there is greater incentive to purchase electricity from sustainable sources, benefiting consumers with lower electricity acquisition costs. Thus, this study seeks to compare two distinct market models: Brazil and Portugal. While the former is in the process of opening, the latter is already well-established, with suppliers and consumers interacting freely in the energy contracting process. The historical evolution of these markets will be explored, followed by an analysis of the tariff characteristics currently established in each nation.

## 1 Introduction

A large portion of the world's electricity is produced from non-renewable energy sources, originating from the burning of fossil fuels. However, this generates a series of serious consequences for human health and the environment, with a significant amount of toxic gas emissions into the atmosphere that, in the long run, lead to worrisome problems such as climate imbalance.

Therefore, it is necessary to adopt a global energy transition process, not only by replacing non-renewable energy sources with sustainable ones but also by adopting a series of changes in the models of electricity production, distribution, and consumption, aiming to achieve greater sustainability.

In this context, it is evident that Brazil, despite increasingly standing out as a renewable energy power, still has much to develop in establishing itself as a reference in energy transition. The country currently has a predominantly renewable electricity matrix, with a focus on hydro, wind, solar photovoltaic and biomass sources, and is aligned with the goals of Sustainable Development Goal (SDG) No. 7 of the United Nations (UN) 2030 Agenda. However, when it comes to the management and operation of efficient energy markets, the country still has a long way to go, as it is currently undergoing a transformation process toward a fully open market.

It is noteworthy that more advanced markets in their liberalization processes tend to show better energy transition results, with a greater presence of renewable sources in the electricity matrix, lower electricity acquisition costs, and lower levels of external dependence. Portugal, unlike Brazil, is characterized by having an already established and functioning energy market, with production and commercialization activities open to free competition, aiming to achieve greater efficiency in the management and operation of these activities' resources, thereby enabling a better energy transition.

In this sense, this article aims to make a comparative analysis between the energy markets of the countries mentioned above, as Brazil is transitioning to consolidate an open electricity market, while

Portugal already has this structure well defined. Thus, the historical evolution of the energy markets of both countries and their tariff characteristics in terms of comparison will be presented.

## 2 History of the Energy Markets in Portugal and Brazil

Currently, energy commercialization in Portugal takes place in a fully liberalized market, with broad competition and competitiveness. However, to reach its current level, the country went through several transformations. Previously, the electricity market in Portugal was fully regulated and monopolized by EDP in the commercialization sector. Between 1995 and 2006, a gradual transition process began, similar to what had already occurred in other European countries, toward the opening of the energy market.

This progress started with the publication of the European Directive 96/92/EC, which established common rules for the internal electricity market across the European Union, and Decree-Laws No. 182/95 to 188/95, which determined a new organizational model for the Portuguese electricity sector. These regulations constitute the first energy package of the European Union, which aimed to gradually open the electricity and gas markets to free competition, as they were still monopolies. Through these decrees, ERSE (Energy Services Regulatory Authority) was created as an independent entity responsible for regulating the electricity sector. Moreover, the Portuguese electricity sector was established in two models: the SEP (Public Service Electricity System) and the SEI (Independent Electricity System).

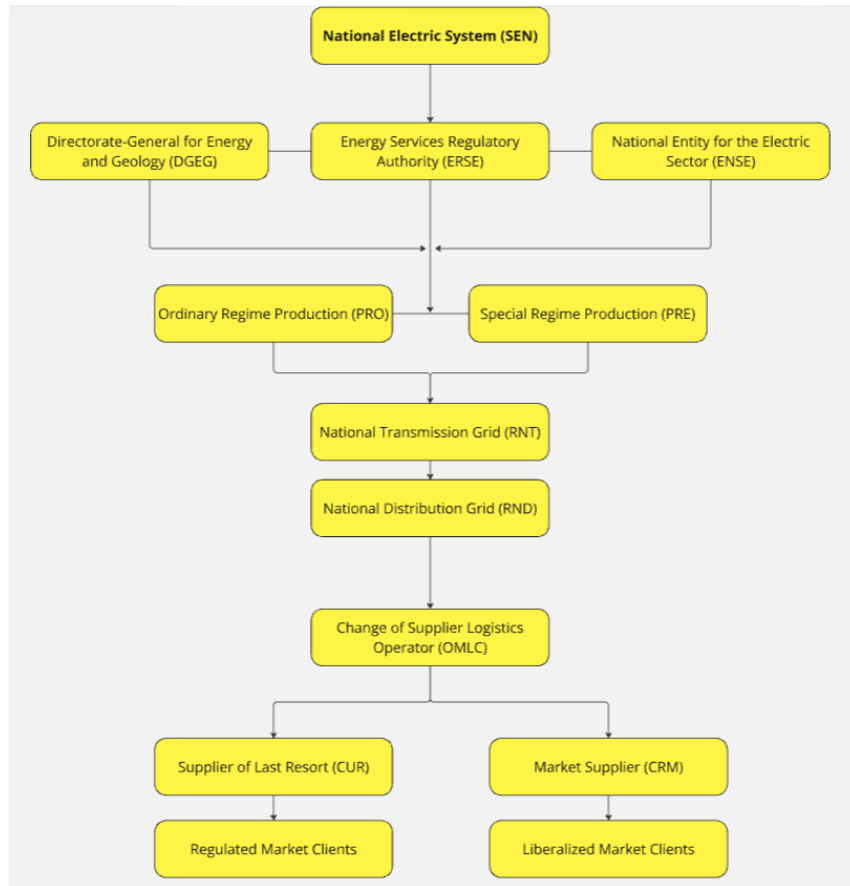
The first is characterized by a market regulated by ERSE with only one buyer: REN (National Energy Grids), which is responsible for transmitting electricity throughout the country. The distribution and commercialization sectors in SEP were the responsibility of EDP Distribution, while producers could commercially interact with REN through CAEs (Power Purchase Agreements), long-term contracts aimed at attracting investment in power plants. Finally, in this system, energy supply and tariff uniformity were mandatory throughout the entire country.

On the other hand, the SEI is composed of the Unbound Electricity System (SENV) and Special Regime Production (PRE). The first refers to producers and consumers who are not linked to SEP and who commercially interact through freely negotiated bilateral contracts, marking the opening of the market. PRE is formed by production units that generate electricity through renewable sources or cogeneration. In this independent system, commercialization was the responsibility of a private company within the EDP group, created to operate in the free market.

Following the process of opening the Portuguese electricity market, the second energy package was introduced, granting industrial and domestic consumers the freedom to choose the most favorable electricity supplier for themselves. In this regard, Decree-Laws No. 184/2003 and 185/2003 were published, replacing the previously mentioned 1995 regulations, with the aim of evolving the legislation and structure of the National Electricity System (SEN) towards a market regime open to competition, based on Directive 2003/54/EC. These documents established the creation of MIBEL (Iberian Electricity Market), which aims to integrate the electrical systems of Spain and Portugal, providing benefits to consumers in both nations. Through this market, consumers in Portugal can purchase electricity from producers in Spain, for example, and vice versa. These transformations were consolidated in Decree-Laws No. 29/2006 and 172/2006, which determined the organization of electricity markets, continuing the market opening process and forming the basis for Portuguese legislation to this day.

Subsequently, the third energy package was published, with Directive 2009/72/EC, which intensified the liberalization process of the electricity market by separating production, transmission, and commercialization of energy, and by increasing consumer rights in the retail market.

All the previously mentioned norms and legislation, despite having undergone changes over the years, are duly consolidated and have enabled Portugal to have the following structure of the National Electricity System, presented in **Figure 7**.



**Figure 7** - Current structure of the SEN [adapted from MARTINS (2020)]

Therefore, the market has fully consolidated, allowing all consumers in the country to freely contract, and operators to compete freely and equally regarding prices and commercial conditions. With the publication of Decree-Law No. 104/2010 of September 29, the timetable for the elimination of Final Customer Sale Tariffs (TVCF) for HV, MV, LV, and LVSS customers was established, marking the end of the transition period, during which all customers must have their electricity supplied through the free market, with some exceptions supplied by the Supplier of Last Resort (CUR). Finally, Decree-Law No. 75/2012 of March 26, in a similar manner, put an end to these regulated tariffs for LV customers. Thus, after a transition period (initially set for 2015 but postponed to 2025), all consumers in Portugal participate in the open energy market, freely contracting, and operators competing freely and equally regarding prices and commercial conditions.

Thus, the electricity market in Portugal can currently be subdivided into two segments: the regulated market, where transmission and distribution of electricity are natural monopolies, and the production and commercialization of energy, which are in an open market, subject to free competition, with the economic rationale of producing greater efficiency in the management and operation of these activities.

In the electricity production sector, the open market operates as a wholesale market, which can be characterized as a business model that buys a certain product and sells it to another type of business.

In the electricity sector, market agents in production are responsible for selling electricity to large industrial consumers and/or electricity suppliers. On the other hand, in the electricity commercialization sector, the market is characterized by being a retail market, meaning business models that acquire a certain product and sell it to an end consumer. In the electricity sector, suppliers (who purchase energy in the wholesale market) are responsible for selling the energy to final consumers, representing a retail market.

In this liberalized market, electricity contracting can take place in various ways, such as the daily market (contracting for the next day), intraday market auctions (closer to real-time), and the forward market (for longer terms), for example.

It is possible to make a brief comparison with the timeline of the Brazilian electricity sector and observe certain similarities. The Brazilian electricity sector has not always had the structure it maintains today. Until the early 1990s, there was a strong centralizing policy, in which the sector was marked by extensive state control, coordinated by Eletrobras, starting in the 1960s. However, from the 1990s onwards, the sector began to be privatized, with economic reforms aimed at increasing market efficiency and competitiveness.

This was carried out through various laws, among which the most notable is Law No. 8.987/95, popularly known as the Concessions Law, in 1995, which initiated the participation of private companies in electricity services through public tenders. In the same year, the Wholesale Energy Market (MAE) was established, functioning as a trading and contracting environment for electricity between generating and distributing agents. In the following years, there were privatizations of electricity companies and the founding of the National Electric Energy Agency (ANEEL), the body responsible for regulating, supervising, and mediating the Brazilian electricity sector.

Although there were transformations aimed at restructuring the electricity sector, the growing demand for electricity was not accompanied by supply capacity, resulting in a fragile system with little economic efficiency due to the lack of a free environment for energy contracting and sales. In this context, the New Electricity Sector Model was established in 2003.

The model had guiding principles of energy security, tariff moderation, and universal access to services. Moreover, all demand, both from distributors and free consumers, must be met through commercialization contracts by agents associated with the Electricity Commercialization Chamber (CCEE).

Commercialization is the link between power plants and final consumption in the Energy Market, which can be divided into two parts: the Regulated Contracting Environment (ACR), consisting of captive consumers, and the Free Contracting Environment (ACL), frequented by free consumers.

In the ACR, captive consumers must purchase electricity from their respective distribution concessionaires and pay only one bill per month per consumer unit, encompassing government-set tariffs and distribution and generation services.

On the other hand, in the ACL, free consumers can purchase electricity directly from generators or suppliers through freely negotiated bilateral contracts. Billing also differs from the ACR, where each consumer unit must pay a bill for distribution services to its respective concessionaire, with a tariff regulated by the government, and must also pay one or more bills for the electricity purchase itself, defined by the bilateral contract between the consumer and generator/supplier. Participants in the ACL include consumers with a demand equal to or greater than 3 MW and a voltage equal to or greater than 69 kV; demand equal to or greater than 500 kW, at any supply voltage level, provided that the energy purchased is from micro or small hydroelectric plants or renewable sources such as solar, wind, and biomass; and, starting in 2024, any consumer unit in group A (voltage equal to or greater than 2.3 kV), regardless of contracted demand, may participate in the free contracting environment.

Thus, it is evident that there are several similarities in the development of both energy markets. From a market that was fully regulated and marked by extensive state control, to the opening of the

market, which has already been fully achieved in the European country but is still in transition in Brazil. Nevertheless, the presence of regulatory bodies such as ERSE in Portugal and ANEEL in Brazil, which regulate and organize the electricity sector, and energy contracting environments with freely negotiated bilateral contracts, is observed. Regarding these, it is noted that the transition from a state and fully regulated market occurred much earlier in Portugal than in Brazil, which is still undergoing a gradual process. However, it is understood that the direction for commercialization in the Brazilian electricity sector is the establishment of open energy markets for all spheres, providing greater efficiency, greater security for consumers, and offering better cost-benefit options for acquiring electricity.

### 3 Tariff Analysis of Energy Markets

Having presented the history of the energy markets in Portugal and Brazil, we will now outline some regulatory characteristics to understand the possible similarities and/or differences between the two countries. For the analysis of both countries, documents from the regulatory entities were used as a basis, namely: ANEEL Normative Resolution No. 1,000, dated December 7, 2021, and ERSE Tariff Regulation, dated May 2020.

#### 3.1 Consumer Units

In both countries, the division of consumer units is based on voltage levels. In Brazil, the division is made into two groups, A and B, and their subgroups. Group A consists of "consumer units with a connection voltage greater than or equal to 2.3 kV, or served by an underground distribution system with a voltage lower than 2.3 kV," and is subdivided into subgroups A1, A2, A3, A3a, A4, and AS, depending on the voltage level or the supply (underground). Group B, in turn, consists of "consumer units with a connection voltage lower than 2.3 kV," subdivided into B1 (residential), B2 (rural), B3 (other classes), and B4 (public lighting).

In Portugal, consumer units are divided into LV (Low Voltage), MV (Medium Voltage), HV (High Voltage), and VHV (Very High Voltage), with the following definitions:

- a) VHV - Very High Voltage: Phase-to-phase voltage with an effective value greater than 110 kV.
- b) HV - High Voltage: Phase-to-phase voltage with an effective value greater than 45 kV and less than or equal to 110 kV.
- c) MV - Medium Voltage: Phase-to-phase voltage with an effective value greater than 1 kV and less than or equal to 45 kV.
- d) LV - Low Voltage: Phase-to-phase voltage with an effective value less than or equal to 1 kV:
  - i. SLV - Special Low Voltage: Low Voltage supplies with contracted power greater than 41.4 kW.
  - ii. NLV - Normal Low Voltage: Low Voltage supplies with contracted power less than or equal to 41.4 kVA.

## 3.2 Tariff Periods and Tariff Modes

According to Article 34 of ERSE's Tariff Regulation, there are three types of tariff periods. The first is the quarterly period: Period I (January 1 to March 31), Period II (April 1 to June 30), Period III (July 1 to September 30), and Period IV (October 1 to December 31). The second is the hourly period: Peak hours, Full hours, Normal Off-Peak hours, and Super Off-Peak hours. Lastly, there are seasons: High Season, Medium Season, and Low Season. Of these three classifications, the most common are the hourly periods, and the duration of each period depends on the cycle chosen by the consumer, which can be daily, weekly, or weekly by seasons.

In Brazil, there is only one division of tariff periods, the hourly periods, which are:

- a) **Peak Tariff Period:** A period consisting of 3 consecutive daily hours defined by the distributor, considering the load curve of its electrical system, approved by ANEEL for the entire concession or permission area, not applicable on weekends and national holidays.
- b) **Intermediate Tariff Period:** A period of two hours, one immediately before and one immediately after the peak period, applied only to Group B.
- c) **Off-Peak Tariff Period:** A period consisting of the set of consecutive daily hours complementary to those defined in the peak and, for Group B, intermediate periods.

Based on the tariff periods, the tariff modes to be adopted by consumers are then defined. In both countries, there are four types of tariff modes. In Portugal, they are simple tariff, bi-hourly tariff, tri-hourly tariff, and tetra-hourly tariff. In Brazil, they are conventional tariff mode, white tariff mode, green tariff mode, and blue tariff mode. This information, as well as their definitions, are presented on **Table 1**.

Here, there is a significant difference between the two energy markets. In Brazil, Group B consumer units can only choose between the conventional or white tariff modes, and those belonging to Group A must choose between the blue or green tariff modes (except for those that choose to be classified as Group B consumers). In the latter case, installations with a connection voltage of at least 69 kV must necessarily opt for the blue tariff mode. In Portugal, however, consumer units, regardless of the voltage level, can choose from all tariff methods. In other words, customers can opt for the situation that is most advantageous both energetically and economically, as depending on the tariff mode chosen, they can manage their energy consumption to use more when the tariff is lower, and less when the tariff is higher.

<b>Brazil</b>	<b>Portugal</b>
<b>Conventional Tariff Mode:</b> Characterized by a single tariff for energy consumption, without time segmentation during the day.	<b>Simple Tariff:</b> the same price for electricity at all hours of the day.
<b>White Tariff Mode:</b> A tariff for the Peak period, a tariff for the Intermediate period, and a tariff for the Off-Peak period.	<b>Bi-Hourly Tariff:</b> one tariff for off-peak hours and one tariff for non-off-peak hours.
<b>Green Tariff Mode:</b> A tariff for demand (without time segmentation), a tariff for energy consumption during the Peak period, and a tariff for energy consumption during the Off-Peak period.	<b>Tri-Hourly Tariff:</b> one tariff for the Off-Peak period, one for the Full period and another one for the Peak period.
<b>Blue Tariff Mode:</b> A tariff for demand during the Peak period, a tariff for demand during the Off-Peak period, a tariff for energy consumption during the Peak period, and a tariff for energy consumption during the Off-Peak period.	<b>Tetra-hourly tariff:</b> similar to the previous one, but with the subdivision of off-peak hours into Normal Off-Peak and Super Off-Peak.

**Table 1** - Tariff Modes options

### 3.3 Billing Variables

Here, the variables commonly used in the billing of the consumer unit, which show a significant difference between the two countries, will be analyzed. These are:

- a) Contracted Power and Measured Power.
- b) Peak Hours Power.
- c) Reactive Energy.

Primarily, according to ANEEL, in Brazil, the Contracted Power must be “obligatorily and continuously made available by the distributor at the connection point, according to the value and duration set in the contract, in kW (kilowatts)”. and the Measured Power is “the highest demand of active power injected or required from the distribution electrical system by the load or generation, measured and integrated in 15-minute intervals during the billing period, in kW (kilowatts)”. The values of these metrics directly influence the monetary expenses of the consumer unit, since one will pay for the highest amount between the Contracted Power and the Measured Power. Therefore, having a Contracted Power lower than needed will result in overcharge penalties, while having a higher amount will mean paying in excess for something unused. For this reason, a request can be made to the distributor to change this value, but no more than one reduction in demand (power) is allowed within a 12-month period. In Portugal, Contracted and Measured Power has the same previous definitions, except that the Contracted Power value is automatically updated to the highest power value measured in the last 12 months.

Peak Hours Power is, for consumer units in Brazil, the measured demand value during the Peak tariff period, and in Portugal, it is the ratio between the electrical energy consumed during Peak hours and the number of hours in the respective period.

Finally, ANEEL defines Reactive Energy as “the energy that circulates between the various electric and magnetic fields in an alternating current system without performing work, measured in kvarh (kilovolt-ampere-reactive-hour)” and sets a maximum value for this metric so that the Power Factor of the consumer unit is greater than or equal to 0.92 for Group A, subject to a penalty for excess reactive energy. The ERSE Tariff Regulation defines Reactive Energy as inductive if consumed and capacitive if supplied to the grid. Its billing “only occurs after eight months of electricity consumption in the following situations: a) New installations; b) Upon customer request, following a variation in the contracted power of the installation by at least 50%. Furthermore, Inductive Reactive Energy measured during Off-peak Hours will be subject to billing if it exceeds “30% of the active energy consumed in the same period,” with the applicable price depending on tiers, based on the ratio between Inductive Reactive Energy and Active Energy in the same period:

- a) Greater than or equal to 30% and less than 40%.
- b) Greater than or equal to 40% and less than 50%.
- c) Greater than 50%.

### 3.4 Main Tariffs

In Brazil, the tariff is the “monetary value set by ANEEL, determined in R\$ (Reais) per unit of electricity or power demand,” as follows:

- a) Energy Tariff – ET: the unit monetary value set by ANEEL, in R\$/MWh (Reais per megawatt-hour), used for monthly billing of energy consumption.

- b) Distribution System Usage Tariff – DSUT: the unit monetary value set by ANEEL, in R\$/MWh (Reais per megawatt-hour) or in R\$/kW (Reais per kilowatt), used for the monthly billing of the consumer and other users of the electricity distribution system for the use of the system.

In Portugal, ERSE defines the Grid Access Tariff, a sum of the tariffs for Global System Use, Transmission Grid Use, and Distribution Grid Use (all set by ERSE), which is paid by all consumers, regardless of whether they are in the regulated or liberalized market. The Grid Access Tariffs applicable to VHV, HV, MV, and SLV consumers consist of the following prices:

- a) For contracted power, defined in Euros per kW per day.
- b) For peak hour power, defined in Euros per kW per day.
- c) For active energy, defined in Euros per kWh.
- d) For reactive energy, defined in Euros per kVArh.

The active energy prices for VHV, HV, and MV clients vary according to the hourly periods in the weekly cycle, shown on the **Table 23** (Table 8.1 of Article 34 of Tariff Regulation). For LV, the daily cycle, shown on the **Table 3** (Table 8.2 of Article 34 of Tariff Regulation), may also be taken into consideration. The reactive energy prices differ for inductive and capacitive reactive energy.

Winter Legal Time	Summer Legal Time
Monday to Friday Peak: 5 h/day Full: 12 h/day Normal Off-Peak: 3 h/day Super Off-Peak: 4 h/day	Monday to Friday Peak: 3 h/day Normal Off-Peak: 3 h/day Full: 14 h/day Super Pff-Peak: 4 h/day
Saturdays Full: 7 h/day Normal Off-Peak: 13 h/day Super Off-Peak: 4 h/day	Saturdays Full: 7 h/day Normal Off-Peak: 13 h/day Super Off-Peak: 4 h/day
Sundays Normal Off-Peak: 20 h/day Super Off-Peak: 4 h/day	Sundays Normal Off-Peak: 20 h/day Super Off-Peak: 4 h/day

**Table 23 - Weekly Cycle**

Winter Legal Time	Summer Legal Time
Peak: 4 h/day Full: 10 h/day Normal Off-Peak: 6 h/day Super Off-Peak: 4 h/day	Peak: 4 h/day Full: 10 h/day Normal Off-Peak: 6 h/day Super Off-Peak: 4 h/day

**Table 3 - Daily Cycle**

The Grid Access Tariffs applicable to LV consumers, in turn, consist of the following prices:

- a) For contracted power, in Euros per day.
- b) For active energy, defined in Euros per kWh.

The prices for contracted power in LV vary according to the schedules shown on the **Table 4** (Table 12 of Article 52 of the Tariff Regulation). If the contracted power is less than 20.7 kVA, the prices for active energy will be broken down into two or three time periods or may not have any time differentiation. If it exceeds 20.7 kVA, the prices will be differentiated across three time periods.

Tariff Options	Contracted Power Levels (kVA)
BTN ≤ 20.7 kVA	
Simple Tariff	1.15 - 2.3 - 3.45 - 4.6 - 5.75 - 6.9 - 10.35 - 13.8 - 17.25 - 20.7
Bi-hourly Tariff	1.15 - 2.3 - 3.45 - 4.6 - 5.75 - 6.9 - 10.35 - 13.8 - 17.25 - 20.7
Tri-hourly Tariff	1.15 - 2.3 - 3.45 - 4.6 - 5.75 - 6.9 - 10.35 - 13.8 - 17.25 - 20.7
BTN > 20.7 kVA	27.6 - 34.5 - 41.4

**Table 4** – Contracted Power Levels (kVA) for NLV

## 4 Conclusions

Although Portugal already has a fully open energy market, while Brazil is still in the process of opening its own, certain historical similarities can be observed between their respective energy markets, particularly regarding the transition from a fully regulated market, through state control, to a more liberalized scenario. These similarities could provide an opportunity to assess which measures may or may not work when applied to Brazil, to ensure the principles, set out by the New Electric Sector Model, that is energy security, tariff moderation and universal access to services.

Not only were presented the two countries' likenesses, but also their differences, specifically those regarding the tariffs of the energy markets, e.g. the definition of their consumers, along with the Tariff Modes one can choose from. Additionally, the Billing Variables were analyzed, through which it was possible to observe how consumers are charged for electricity consumption. Although both countries have the same definitions for Contracted Power and Measured Power, and a similar definition for Peak Hours Power, the billing system is different. In Portugal, the consumer pays for Contracted Power and Peak Hours Power, with the Contracted Power being automatically adjusted to the highest Measured Power value in the last 12 months. In contrast, a consumer unit in Brazil will be charged based on the higher value between Contracted Power and Measured Power, being subject to an overcharge penalty if the latter exceeds the former. Otherwise, the consumer will pay for unused capacity. For this reason, a request can be made to the distributor to change the Contracted Power value, but no more than one reduction is allowed within a 12-month period. Therefore, the importance of conscious electricity use is evident, thus avoiding unnecessary expenses, both monetary and energy-wise. Lastly, the main tariffs that make up the prices of the electrical quantities used in Brazil (Energy Tariff and Distribution System Usage Tariff) and in Portugal (Grid Access tariffs) were presented.

Therefore, in the market transition process Brazil is undergoing, it is necessary that its opening be carried out in a way that provides greater efficiency, greater security for consumers and offering better cost-benefit options for acquiring electricity.

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# A comparison review of levelized cost of hydrogen produced from renewable sources: an opportunity for Brazil to become a protagonist on the hydrogen market

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## Abstract

Amidst climate change and the need to diversify the energy matrix, hydrogen emerges as a solution to reduce greenhouse gas emissions and promote integration across various sectors constituting the global economy. Currently, the majority of hydrogen is derived from steam-reforming processes of fossil fuels, but it can also be produced through water electrolysis using renewable energy sources such as solar photovoltaic, wind, or hydro. This paper aims to present the levelized cost of low-emission hydrogen production worldwide and illustrate the advantage of production in countries with available renewable sources. For instance, Brazil's renewable energy infrastructure holds a competitive advantage in gas production, potentially reducing costs compared to other locations globally due to high wind and solar capacity factors in its territory. This advantage extends to domestic use, including fertilizer production, refinery operations, and export. Comparing the levelized cost of hydrogen production in various countries, with a combination of different renewable technologies, reveals that the initial cost of implementing these projects is still high but may become economically viable if component prices decrease.

## 1 Introduction

With the increase in population and the continuous use of fossil fuels as the primary source of global energy for decades, the environmental impacts resulting from the use of these fuels, such as greenhouse gas emissions, depletion of natural resources, and climate change, cannot be ignored. Currently, 85% of the world's energy consumption is derived from non-renewable resources including coal, oil, and natural gas, which not only contributes to environmental impacts but also to political and economic crises (Abdalla et al., 2018).

Emerging as a solution for the profound decarbonization of the global economy, hydrogen has the potential to become a significant fuel and energy storage vector for the energy transition. Hydrogen is the most abundant element in the universe and the simplest, consisting of only one atom with one proton and one electron (Momirlan & Veziroglu, 2005). It possesses several advantages, such as its high energy density, it provides three times more energy than gasoline combustion per unit of mass, and it offers the possibility of being produced locally, thus reducing countries' dependence on external energy suppliers (Liu et al., 2022). The main uses of hydrogen are in refineries and the industrial sector to produce

ammonia, methanol, and in steel production. However, hydrogen also has the capacity to be used as chemical raw materials, burned for heating, used as a reactant to produce synthetic fuels, or converted into energy via fuel cells (Oliveira et al., 2021).

As renewable energy sources, such as solar photovoltaic and wind, are expected to contribute to around 43% of global energy generation by 2030, up from the current 28%, (IEA, 2022) the need for energy storage becomes crucial to ensure the security and reliability of electrical systems, given the high intermittency associated with these sources. Hydrogen is thus considered an essential technology for large-scale and long-term storage of renewable sources (Maggio et al., 2019). Due to its multifunctionality, hydrogen is seen as a resource to promote the coupling of fuel, electric, industrial, and other markets (EPE, 2021).

Given this scenario of climate change and the need to shift the global primary energy source, governments worldwide are working on roadmaps and implementation programs to encourage the development of the hydrogen economy produced through water electrolysis (Wappler et al., 2022). Despite being described as one of the most competitive countries in low-emission hydrogen production, with a leveled cost projected to be below US\$1.50/kg by 2030 (McKinsey & Company, 2022), Brazil still lacks a defined strategy. To address the topic of hydrogen in the Brazilian energy chain, several studies by the Energy Research Company (EPE) in conjunction with the Ministry of Mines and Energy (MME) have been published in recent years. Among these studies, "Bases for Consolidation of the Brazilian Hydrogen Strategy" and the National Energy Plan - 2050 stand out (EPE, 2020, 2021).

Hydrogen is classified by different colors, which indicate the production method. However, this color classification does not specify the exact number of emissions generated in the production of low-carbon hydrogen and can cause ambiguities, as the same color can be used to classify different technologies. Therefore, various efforts are being made worldwide for the certification of hydrogen based on emission accounting criteria and delineation of operational limits. The IEA recommends the use of the term "low-emission hydrogen".

Certification is a priority for countries intending to commercialize hydrogen, as it provides transparency to buyers and better access to information. Among the main ongoing initiatives, notable ones include CertifHy, certification from Australia, and the International Partnership for Hydrogen and Fuel Cells in the Economy. These certifications differ on specific points, mainly regarding the clean production technologies to be considered initially. Nevertheless, it is expected that the standards will converge in their final versions, ensuring the universality of hydrogen certification (GESEL, 2023; IEA, 2023b; IPHE, 2023; World Energy Council, 2022).

Currently, hydrogen is mainly consumed by refineries and the chemical industry to remove impurities, especially sulfur, and as a raw material for the synthesis of ammonia and methanol, respectively. The demand for hydrogen reached 94 million tons in 2021. It is important to note that the hydrogen currently used is almost entirely derived from fossil fuels, resulting in significant CO<sub>2</sub> emissions. The refinery sector alone was responsible for emitting 200 million tons of CO<sub>2</sub> in 2021 (IEA, 2023a). In addition to the sectors mentioned earlier, where replacing existing hydrogen production processes with its sustainable alternatives will lead to significant reductions in greenhouse gas emissions, other sectors of the global economy can benefit from hydrogen to reduce their respective emissions. Notably, transportation and heating are prominent among these sectors.

Nowadays, the principal challenges and barriers to the introduction of green hydrogen are the elevated costs of production, lack of an existing value chain and international standards (Scita et al., 2020). To overcome these technological and economic barriers, significant political incentives are needed to help offset the high initial costs associated with hydrogen production and infrastructure, stimulating investments and accelerating widespread adoption.

The main objective of the article is to present the leveled cost of low-emission hydrogen production and the competitive advantage that Brazil possesses in its production. To achieve this, the article is summarized as follows: in section 1 the need for changes in energy matrix and the challenges and barriers to the introduction of the hydrogen in global economy are introduced and discussed. The

section 2 presents the potential of renewable resources in Brazil, as well as the demand for hydrogen in sectors that can benefit from the reduction in the cost of low-emission hydrogen. In section 3 the different methods of producing hydrogen, with focus on hydrogen produced by electrolysis using renewable energy are explained, while in section 4 various studies from different renewables sources are analyzed, focusing on obtaining the levelized cost of production. The last section is a summary of the more important conclusions about the green hydrogen development.

## 2 Hydrogen Production Potential in Brazil

Brazil is the largest South American country and the fifth-largest country in the world, as well as an economic and political powerhouse in South America. One of the country's great advantages for energy potential is its location in different climatic zones, with high wind and solar capacity factors. In 2023, wind farms reached 31 GW of installed capacity, now representing 13% of the electrical matrix, while photovoltaic plants totaled 45 MW, accounting for around 19% of the national electrical matrix. This growth in installed capacity of intermittent renewable plants in Brazil is still expected for many years, with the projection of reaching 47% of the installed capacity of the system in 2040 (ABEEólica, 2024; McKinsey & Company, 2022).

In addition to the enormous potential of intermittent renewable energies, hydroelectric generation is a major contributor to renewable energy production in the country. The Brazilian electrical matrix has approximately 85% participation of clean energy. Brazil is also a reference in biomass utilization, whether for biogas production or electricity generation, representing 8% of the electrical matrix in 2023 (ABSOLAR, 2023). Another factor that makes Brazil a consolidated market in the scope of alternative and clean energy is the significant role of ethanol in the Brazilian energy matrix, standing out in the global biofuel scenario.

Brazil is in a privileged position to excel in the production of low-emission hydrogen, being able to utilize this input to meet both domestic demand and for exportation. The ports located in the Northeast region of the country can play a fundamental role in the energy transition scenario, linking Brazil, a major producer of renewable energies, to global markets seeking clean and sustainable energy sources.

Given this scenario, various green hydrogen hubs (H2V) are being designed to create an ecosystem for the production, transportation, delivery, and end use of hydrogen in applications across different sectors, notably at the ports and industrial hubs of Pecém (Ceará), which have a partnership with the port of Rotterdam, Suape (Pernambuco), Camaçari (Bahia), and Açú (Rio de Janeiro).

## 3 Hydrogen Production

Hydrogen production can be categorized into three main groups: through the combustion of fossil fuels; coal or natural gas gasification with the use of carbon capture and storage; or from renewable energies. Currently, hydrogen is primarily obtained through steam-reforming processes of fossil fuels, with approximately 96% of the total annual production derived from these sources, causing high indirect CO<sub>2</sub> emissions (Guerra et al., 2019). Production from natural gas, without carbon capture and storage, is the main route and accounted for 62% of hydrogen production in 2021, commonly referred to as grey hydrogen. Hydrogen produced from processes with low carbon emissions, especially water electrolysis from renewable energies, accounted for less than 1% (IEA, 2023a).

Electrolysis is a process for producing hydrogen and oxygen through the electrochemical conversion of water and involves the circulation of a direct current between two electrodes separated and immersed in an electrolyte, which is used to increase ionic conductivity. It is the most important method of obtaining hydrogen from water as it is a mature technology and the hydrogen produced has exhibited

high purity, reaching up to 99.999%. The electrolysis cell is the basic element of an electrolytic hydrogen production system, and they can be connected in series or in parallel to form the electrolysis module, or electrolyzer. (Mohammadi & Mehrpooya, 2018; Ursua et al., 2012)

The essential components of a hydrogen production system are renewable energy sources and the water electrolyzer. Electrolyzers can be divided into three categories based on the electrolyte used, the ionic agent (OH<sup>-</sup>, H<sup>+</sup>, or O<sup>2-</sup>), and the operating temperature: alkaline (ALK), proton exchange membrane (PEM), or solid oxide (SOEC). Alkaline electrolysis is recognized as the most mature technology among the mentioned types. The electrolyzer is composed of two electrodes submerged in an aqueous electrolytic solution, usually 20 to 40% NaOH (sodium hydroxide) or KOH (potassium hydroxide), with a diaphragm separating the electrodes in the solution, allowing the passage of water molecules and hydroxide ions. (Carmo et al., 2013; Zhang et al., 2016)

PEM electrolysis is based on proton exchange membrane technology. Unlike alkaline technology, the electrolyte is solid, made of a thin gas-proof polymeric membrane with a strong acidic character due to the presence of sulfonic acid groups. In terms of environmental impact and sustainability, the PEM electrolyzer is one of the preferred methods for converting renewable energies into pure hydrogen, and it features rapid response, high efficiency, compact design, and high outlet pressure. (Chi & Yu, 2018; Shiva Kumar & Himabindu, 2019). Both ALK and PEM electrolyzers operate at low temperatures, typically below 100°C, while the SOEC electrolyzer operates at temperatures above 500°C, with water in the form of steam. Due to this high temperature, sealing between the anode and cathode chambers in SOEC electrolyzers becomes complicated for long-term operations, increasing the risk of ceramic electrolyte fracturing (Sapountzi et al., 2017).

The main advantages of alkaline electrolysis are low cost, due to the use of non-precious electrodes, and long-term stability. Conversely, the PEM electrolyzer must use catalysts with noble materials in its composition, which, along with the high cost of polymeric membranes, limits the commercialization of this type of electrolyzer in the short term. The solid form of the electrolytes in PEM and SOEC electrolysis allows for a more compact configuration, and operation at different pressures is feasible. This solid nature allows the system to be more dynamic than alkaline electrolyzers, with a faster response for applications with variable loads. One of the advantages of SOEC technology, related to its high operating temperature, is the possibility of producing synthetic gas through co-electrolysis of hydrogen and carbon dioxide mixtures. This gas can be converted into methanol or other hydrocarbons, contributing to renewable energy storage and reducing CO<sub>2</sub> emissions. However, the degradation and lack of stability resulting from the high temperature of SOEC electrolyzers is a challenge that still needs to be resolved for the technology to be commercialized on a large scale (Kim et al., 2015; Tao et al., 2014; Zeng & Zhang, 2010). In Table 1, the major advantages and disadvantages from each different type of production are described.

**Table 1: Advantages and disadvantages of ALK, PEM and SOEC electrolyzers**

Specification	PEM	ALK	SOEC
Advantages	Compact and simple design Quick start and response High H <sub>2</sub> purity Suitable for Load Fluctuation	Stable and established in the market Low capital cost No use of noble materials	High efficiency Low capital cost
Disadvantages	Use of noble materials High membrane cost Low durability Acidic environment	Corrosive Electrolyte Low H <sub>2</sub> purity Slow start Low Current density	Unstable electrodes Security and Sealing issues Voluminous design Use of fragile materials

## 4 Levelized Cost of Hydrogen

The Levelized Cost of Hydrogen (LCOH) is a crucial metric for assessing the economic viability of hydrogen production. This indicator calculates the average cost per unit of capacity (kg H<sub>2</sub>), considering all expenses over the project's life cycle, including initial investments, operational costs, and maintenance (Viktorsson et al., 2017). LCOH is an interesting way to compare different projects, providing a good cost estimate that assists investors, whether domestic or international, in decision-making. Moreover, the use of this metric establishes a global cost benchmark, allowing comparative analyses that reveal how different wind or solar irradiation distributions, energy costs, infrastructure, or even policy support can alter the final cost of hydrogen.

**Table 4: Comparison of Levelized Cost of Hydrogen from different studies**

Reference	Technology	Locality	LCOH (\$/kgH <sub>2</sub> )
(Restrepo et al., 2022)	Concentrated Panels	Solar Brazil	4,32 – 4,55
(Grube et al., 2020)	Concentrated Panels	Solar USA	5,43
(Gutiérrez-Martín et al., 2021)	Solar Photovoltaic	Spain	6,52 – 7,61
(Olateju et al., 2016)	Wind Onshore	Canada	3,37 - 9
(Douak & Settou, 2015)	Wind Onshore	Algeria	1,214
(Rezaei et al., 2020)	Wind Onshore	Afghanistan	2,12 – 2,26
(Khouya, 2020)	EOL Onshore + Concentrated Panels	Marocco Solar	2,36 – 2,66
(Almutairi et al., 2022)	Wind Onshore	Iran	1,38
(Mohsin et al., 2018)	Wind Onshore	Pakistan	5,3 – 5,8
(Rodríguez et al., 2010)	Wind Onshore	Argentina	3,10 – 7,21
(Koholé et al., 2023)	Wind Onshore	Cameroon	4,38 – 6,51
(Ayodele & Munda, 2019)	Wind Onshore	South Africa	1,4 – 39,55
(Dinh et al., 2021)	Wind Onshore	Ireland	5,4
(Franco et al., 2021)	Wind Onshore	Portugal	2,17 – 5,35
(Jovan et al., 2022)	Hydric	Slovenia	3,93 – 10,45
(Nasser et al., 2022b)	Solar Photovoltaic + Wind	Egypt	4,54 – 7,48
(Nasser et al., 2022a)	Solar Photovoltaic + Wind	Egypt	3,73 – 4,65
(Wang et al., 2022)	Wind + Biomass	China	4,16
(Gökçek & Kale, 2018)	Solar Photovoltaic + Wind	Turkey	7,53 – 7,87
(Tiam Kapen et al., 2022)	Solar Photovoltaic + Biogas	Cameroon	0,15 – 7,66
(Song & Ozkan, 2010)	Ethanol	USA	2,69 – 4,27
(Khamhaeng et al., 2021)	Ethanol	Thailand	1,58 – 3,24

After investigating various studies on hydrogen production systems, the levelized costs of hydrogen described in Table 2 are obtained. Given the values found in the studies, there is significant competitiveness of low-emission hydrogen with hydrogen produced from natural gas with CCUS in current times. Additionally, one can observe the various regions of the world where the studies were conducted, with prices that are compatible even in countries with very low participation in the global energy matrix. These studies also promote different forms of hydrogen consumption, integrating the gas into various important sectors in global decarbonization efforts, using it for long-term storage in remote regions or communities, as well as in public and naval transportation or for household heating. This highlights hydrogen's ability to reduce global dependence on fossil fuels, both economically and politically.

When compared to intermittent electricity generation technologies, the lowest LCOH values were found in systems that use onshore wind energy as a source for water electrolysis. Nevertheless, many of the variables that must be included in the calculation of the levelized cost of hydrogen are estimates from other studies, such as initial investments for turbine purchase and installation, operation costs, and maintenance. This can cause uncertainty in the final cost.

In studies of hybrid systems, some gaps can also be identified, which may lead to uncertainties in the final cost of hydrogen production. In the case of the hybrid photovoltaic solar and biomass system, a zero cost is considered for obtaining biomass, as it is obtained from residues from the region's livestock activity (Tiam Kapen et al., 2022). However, a risk and inert cost must be stipulated for the supply of these residues, as over the lifespan of the project, the region's livestock activity may change or even cease, potentially causing technical and economic viability issues for the system. Steam reforming of ethanol presents low hydrogen production costs, with values close to those found from natural gas reforming, rendering it an excellent alternative for hydrogen production in the short and medium term.

## 5 Final Considerations

Hydrogen is a disruptive technology capable of significantly altering the global energy market, with the potential for use in various sectors of the world economy. This article provides a review of low-emission hydrogen production methods, along with challenges for global deployment of the gas. Electrolysis technology has gained much interest in recent years, as it offers a viable pathway for transitioning from a fossil fuel-based economy to renewable energy, with hydrogen being an important energy vector and storage medium.

Since the green hydrogen could be produced from different renewable sources, transported and stored in many possible ways, each project must be thought individually, and could be feasible utilizing different configurations. For example, in a fertilizer industry, the hydrogen transport could be made through the ammonia itself, which already have a well-established infrastructure. But in a refinery, the transport utilizing ammonia could bring more costs and processes to the project, being preferred to use another type of transport and storage. That way, each sector that uses the hydrogen as a scape from the fossil fuel economy, have several possibilities and pathways to find the cheapest and safest way to utilize the hydrogen.

Presently, the current price of low-emission hydrogen is already competitive with hydrogen produced from natural gas with CCUS, and projections indicate a downward trend in the coming years, making hydrogen even more accessible. The results indicate that Brazil has immense potential to become a leader in green hydrogen production, and although initial costs pose a challenge, a commitment to sustainable development and the pursuit of innovative solutions can position the country as a reference in hydrogen /production.

## Acknowledgement

The authors would like to thank the financial support granted through FAPESC/CAPES (06/2023 – TO: 2023TR000925).

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# Life cycle assessment in energy recovery from municipal solid waste: A bibliometric analysis and systematic review

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## Abstract

This research presents a review of trends in studies on life cycle assessment applied to energy recovery from municipal solid waste, integrated with life cycle cost analysis, levelized cost of energy, and eco-efficiency. The methodology used was bibliometric analysis and systematic review which applied the PRISMA method. The selected database was the Web of Science. Bibliometric analysis was performed to identify the main countries and the scientific collaboration between them, and the co-occurrence of authors' keywords. The analysis showed that the countries with the most partnerships are China, the United States, and Italy. The most frequently cited author keywords were “life cycle assessment”, “life cycle analysis”, “energy recovery”, “anaerobic digestion”, “circular economy”, “sustainability”, “life cycle”, “recycling”, “energy”, “incineration”, “waste management” and “biogas”. It was identified that there is a growing trend of studies from 2015 onwards and this reflects the relevance of LCA in waste treatment systems. However, the analysis also highlighted a gap in the literature on eco-efficiency, with relatively few studies focusing on this aspect of energy recovery from MSW.

**Keywords:** Municipal solid waste; Life cycle assessment; Life cycle cost; Levelized cost energy; Eco-efficiency

## 1 Introduction

Population growth, urbanization, economic activity, and consumption have led to a significant increase in municipal solid waste (MSW) produced, which has now become one of the significant environmental challenges globally (USEPA, 2022). According to the World Bank, in 2020, it was estimated that the world generated 2.24 billion tons of solid waste, resulting in a footprint of 0.79

kilograms per person per day. Projections indicate that annual waste generation could surge by 73% compared to 2020 levels, potentially reaching 3.88 billion tons by the year 2050 (World Bank, 2022).

Other factors that contribute to the increase in MSW are related to its composition and characteristics, which influence its variation. The composition of MSW varies significantly from one municipality to another and from one country to another. This variation mainly depends on lifestyle, economic conditions, waste management regulations and industrial structure (Abdel-Shafy & Mansour, 2018).

This trend is also reflected in the growing demand for energy, which has led to an increase in fossil fuel consumption and waste production (Lisbona, Pascual & Pérez, 2022). These issues, increased waste production and energy demand, have a negative impact on the environment and sustainability (Nubi, Morse & Murphy, 2022). In this context, there is an urgent need to explore alternative sources of renewable energy to replace fossil fuels and meet the growing demand (Sharma & Chandel, 2021).

MSW can be used as a raw material for generating energy as a renewable source, which has led to numerous research efforts worldwide to produce energy on an industrial scale (Hasan, et al., 2021). Therefore, an environmental evaluation tool like life-cycle assessment (LCA) is necessary to evaluate the environmental impacts of MSW. LCA is widely adopted internationally to scientifically assess environmental performance (Zhour, et al., 2018). LCA is an environmental management tool used to evaluate a product, activity, or service at all stages of its life cycle, from the acquisition of raw materials through processing, manufacturing, distribution, use, possible reuse and recycling, to final waste management (Khandelwal, et al., 2019).

Several LCA studies have been conducted to evaluate the environmental benefits and drawbacks of energy recovery technologies. Chen, et al. (2019) performed a LCA on a waste disposal technology regarding the integrated treatment of MSW and sewage sludge (SS) in China. In the study carried by Jeswani et al. (2021), the authors used LCA to compare the environmental impacts of chemical recycling of mixed plastic waste (MPW) via pyrolysis with different types of waste management, such as: mechanical recycling and energy recovery.

In the study carried by Sadeleer, Brattebo, and Callewaertthe (2020), the authors analyzed the environmental benefits of two waste management systems for household organic food waste, focusing on recycling through anaerobic digestion (AD) and incineration. The study aimed to determine the environmental profile of the system based on recycling rates, energy efficiency, and GHG emissions.

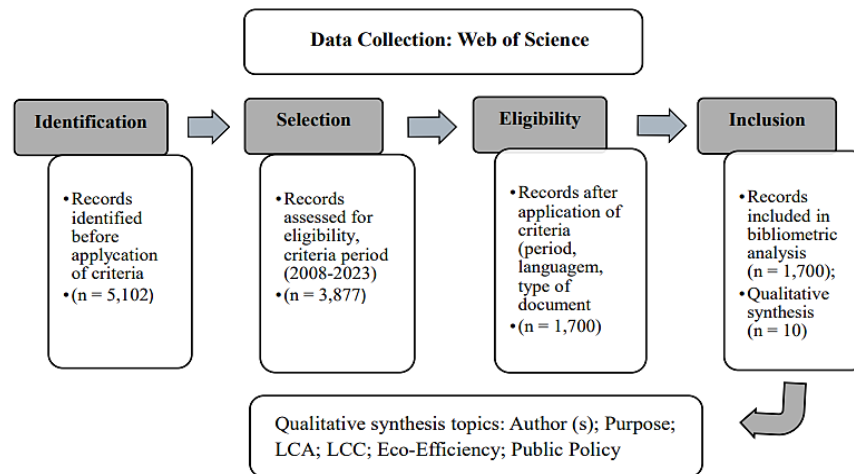
Thus, this study aims to review, through bibliometric and systematic analysis, the research trends on life cycle assessment (LCA), life cycle cost (LCC) and levelized cost of energy (LCOE), in energy recovery from MSW and the relationship of these concepts with eco-efficiency in the context of public policies. It is noteworthy that studies were not identified in the period analyzed that address this approach in an integrated manner, highlighting this gap. Therefore, this research contributes to the discussions within this theme.

## 2 Methodology

A bibliometric analysis and systematic literature review anchored by the PRISMA Meta-analysis (Main Items to Report Systematic Reviews and Meta-analysis) were carried out to identify relevant studies. Meta-analysis aims to critically appraise the findings of relevant peer-reviewed studies (Padilla-Rivera et al., 2023).

The search was carried out in the Web of Science database referring to the period from 2008 to 2023. In the searches, field labels were used for the keywords: ("waste eco-park\*" OR "ecopark" OR "eco-park" AND "municipal solid waste\*" AND "waste-to-energy\*" OR "energy recovery" AND "life cycle assessment" OR "life cycle analysis" OR "life cycle cost" AND "levelized cost of energy" OR "lcoe" AND "eco-efficiency" AND "public policy").

The initial search resulted in 5,102 documents. For refinement, the following parameters were used: document type (articles and reviews), period (the last fifteen years), and language (English). At this stage, 3,877 documents were identified. Additional topic screening resulted in the inclusion of 1,700 items for analysis. For bibliometric analysis, RStudio software, Bibliometrix-package (Aria et al., 2017) and the VOSviewer software (Van Eck & Valtman, 2019) were used. **Figure 1** describes the research steps.



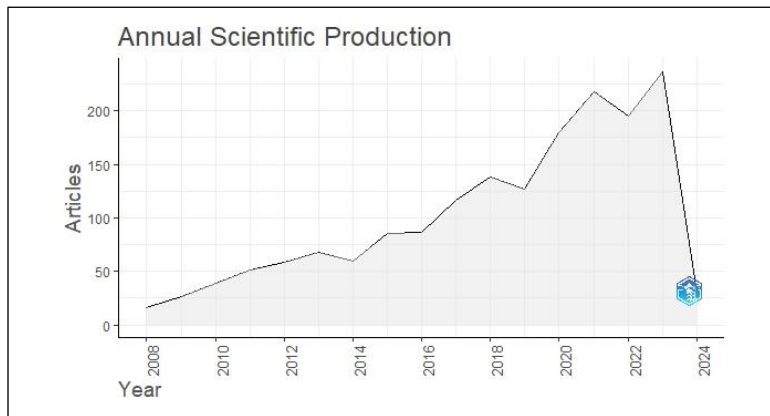
**Figure 1:** PRISMA meta-analysis steps.

## 3 Results and Discussion

### 3.1 Bibliometric Analysis

The bibliometric analysis involved identifying the quantitative evolution of scientific production over the period and identifying relationships between publications, such as co-authorship between countries, the occurrence of author keywords, and main cited sources.

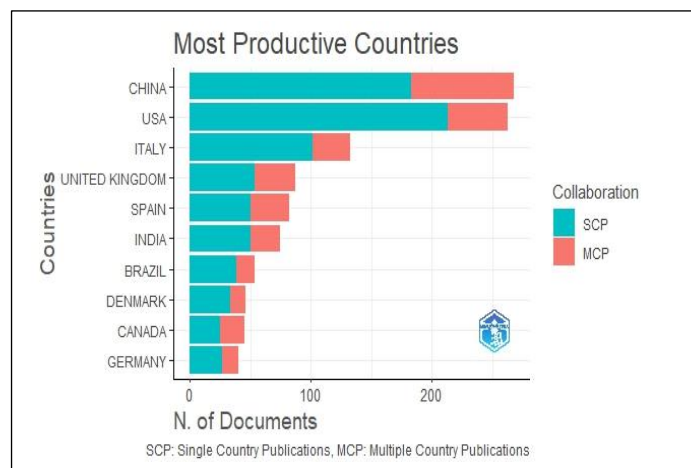
Annual scientific production increased by 4.01% in the period analyzed, with an increase in the number of publications from 2015 onwards, reaching a total of 85 documents. This increase may be linked to the Paris Agreement signed in 2015, a global commitment in which signatory countries committed to reducing greenhouse gas (GHG) emissions and achieving carbon neutrality through climate policies (Li et al., 2022). The continued growth in subsequent years reflects concerns about waste related issues and the search for solutions through research. In addition, this trend highlights the importance of life cycle assessment (LCA) in energy recovery from municipal solid waste (MSW). **Figure 2** illustrates the scientific production during the period analyzed.



**Figure 2: Annual Scientific Production**

The 10 most productive countries in the period, by number of documents in collaboration are: China (268=183-CSP, 85-MCP), USA (263=213-CSP, 50-MCP), Italy (133=102-CSP, 31-MCP), United Kingdom (87=54-CSP, 33-MSP), Spain (82=50-CSP, 32-MCP), India (75=50-CSP, 25-MCP), Brazil (54=39-CSP, 15-MCP), Denmark (46=34-CSP, 12-MCP), Canada (45=25-CSP, 20-MCP) and Germany (40=27-CSP, 13-MCP), **Figure 3**. It is observed that the countries that stood out the most were China, the USA, and Italy in simple and multiple collaborations. The main collaborations are between (China, USA, and Indonesia); (United Kingdom, Spain, France, and Denmark); (Portugal, Greece, Poland, and Ukraine); (Brazil, Colombia, and Cuba).

China, like other countries in Asia, faces problems with increased urbanization and waste production. However, the country has stood out in solutions for energy recovery from waste. China has an installed MSW power generation capacity that is 40% of all Organization for Economic Co-operation and Development (OECD) countries combined (International Energy Agency, 2019). The United States regions without adequate landfill space are developing several advanced MSW energy recovery systems (Mukherjee, et al. 2020). Italy, as part of Europe, is following its environmental legislation. European Union (EU) legislative measures have led member countries to reform their waste legislation and make significant changes to waste management (Chioatto, Khan & Sospiro, 2023).



**Figure 3: Countries Collaboration**



Environment (46), and Energy Policy (45). It is observed that the Journal of Cleaner Production appears with the largest number of publications. However, when analyzing the most cited journals, Resources, Conservation and Recycling stands in first place, with 2,065 citations.

### 3.2 Systematic Review

The Systematic Literature Review was carried out by selecting the main research identified. For this analysis, the period from 2018 to 2023 was considered. The criteria used in this phase involved the identification and selection of the ten main research studies directly related to life cycle assessment, life cycle cost analysis, levelized energy cost, eco-efficiency and public policies. **Table 1** presents the selected studies.

Author's	Purpose	LCA	LCC	LCOE	EE	PP
Banu, et al. (2020)	Bioeconomy in biofuels from microalgae	Y	Y	N	N	N
Rasheed et al. (2022)	Biogas purification and filtration system made of reinforced glass fiber composite material.	Y	N	N	N	N
Chen et al. (2019)	Integrated treatment technology for MSW and sewage sludge	Y	Y	N	N	N
Pereira et al. (2020)	Benefits for vinasse conversion to biogas in Brazil	Y	Y	Y	N	N
Nubi, Morse and Murphy (2022)	Assess the economic viability of WtE using life cycle costing (LCC)	Y	Y	Y	N	Y
Dai and Taghavi (2021)	Production of methane electricity from collected MSW and greenhouse gas assessment	Y	Y	Y	N	Y
Chin, Lee and Woo (2023)	Multi-objective optimization model for optimal MSW settings based on a waste eco-park (WEP) configuration	Y	Y	N	N	N
Tayeh, Alsayed and Saleh (2021)	Incineration technology as a potential WtE option.	Y	Y	Y	N	N
Sridhar et al. (2021)	Review current technologies used to convert food waste into fuel	Y	N	N	N	N
Alizadeh et al. (2020)	Sustainability of two actual wastewater treatment plants using the eco-efficiency	Y	N	N	Y	N

**Table 1:** Main studies on life cycle assessment included in the systematic review  
Abbreviations: **LCA:** Life Cycle Assessment; **LCC:** Life Cycle Cost; **LCOE:** Levelized Cost Energy; **EE:** Eco-Efficiency; **PP:** Public Policy; **Y:** Yes, the study presents the analysis; **N:** Not, the study doesn't present the analysis.

#### 3.2.1 General perspective of life cycle assessment and life cycle cost applied for municipal solid waste

The focus of the studies is directed towards issues related to the increase in energy demand and the need for renewable energy sources, with MSW being an important source of raw material. In this context, the concept of the circular bioeconomy has emerged as an essential component of waste recovery technologies advancing towards a green economy (Banu et al., 2020). In this regard, the various applications of LCA in the recovery of MSW highlight the importance of evaluating the entire process to ensure its sustainability. This includes the production of biofuels derived from microalgae (Banu et al., 2020), integrated MSW treatment, biogas purification (Rasheed et al., 2022), sewage recovery (Chen et al., 2020), and the assessment of energy potential in developing countries (Dai & Taghavi, 2021; Tayeh, Alsayed & Saleh, 2021), among other applications.

In the study carried out by Banu et al. (2020), the authors describe LCA as aligned with the concept of the circular bioeconomy in the biorefinery approach applied to the production of biofuels from microalgae. Microalgae biorefinery is seen as an approach with great potential for achieving a sustainable economy. They emphasize the importance of different sustainability approaches for a microalgae production process, including LCA, life cycle energy analysis, life cycle analysis of carbon dioxide emissions, and other related methods frequently used in the production of biofuels.

Complementing LCA, life cycle cost analysis (LCC) is a life cycle approach that allows for comparative economic cost assessments throughout the waste treatment process (Chen et al., 2019; Pereira et al., 2021; Nubi, Morse & Murphy, 2022). LCC, as an economic measurement tool, enables the evaluation of project viability and the environmental and economic impacts they may generate. In the study conducted by Nubi, Morse, and Murphy (2022), the authors present the results of an LCC-based assessment of the potential economic impacts of adopting WtE systems. Thus, LCA and LCC together allow for comprehensive analysis of process sustainability. In the study by Chen et al. (2019), the authors apply LCC to the integrated treatment of MSW and sewage sludge (SS) in the context of China, demonstrating how integrated analysis can be useful in decision-making.

The different approaches to LCA applications in energy recovery from waste lead to a set of analyses that enable monitoring the entire process flow, identifying possible failures, and developing sustainable solutions. In this context, Chin, Lee, and Woo (2023) proposed a multi-objective optimization model for the sustainable management of MSW based on the waste ecopark (WEP) configuration, a term still not widely explored but essentially incorporating the processes developed by biorefineries (Banu et al., 2020). According to the authors, the WEP model integrates economic, environmental, and social analyses and is based on LCA (Chin, Lee & Woo, 2023).

### 3.2.2 Life Cycle Assessment and Levelized Cost of Energy (LCOE)

MSW project energy analysis allows for the measurement of energy generation potential and associated costs. The levelized cost of energy (LCOE) is an important measure of economic viability used in these studies. To map the potential for energy and biogas generation and evaluate the economic viability of anaerobic digestion of vinasse in UASB reactors, Pereira et al. (2020) conducted a study focusing on the state of São Paulo, Brazil. The authors performed an LCA and LCC, followed by an LCOE analysis. The results indicate that the total energy generation potential for the state was 829 GWh/year. However, the total viable electricity potential was 659 GWh/year, which is equivalent to 80% of the total capacity. Furthermore, 33% of municipalities are economically viable. The energy generated would be sufficient to serve approximately 300,000 inhabitants, demonstrating the importance of integrated analysis.

According to Dai and Taghavi (2021), the potential for electricity generation from MSW depends mainly on the volume of CH<sub>4</sub> removed from the landfill and the conversion efficiency. Thus, the LCOE assists in this process (Nubi, Morse & Murphy, 2022). In their study, the authors evaluated the

performance of energy generation projects from waste based on the LCOE to assess not only energy generation but also economic viability and greenhouse gas emissions.

### 3.2.3 Life Cycle Assessment in eco-efficiency analysis

The analysis of eco-efficiency in projects for generating energy from MSW is still underexplored. According to Alizadeh et al. (2020), eco-efficiency was defined by the World Business Council for Sustainable Development (WBCSD) in 1991 as a management strategy that combines financial and environmental performance to generate value with less environmental impact. The determination of the eco-efficiency index is based on the added value divided by an environmental index. This approach allows for the assessment of the environmental impacts of the life cycle of a production process, as well as the value generated for its stakeholders.

According to the authors, recent studies in several countries, such as Spain, China, and India, have developed analyses focused on eco-efficiency in the treatment of wastewater from WWTPs. In this context, they conducted a study with two real cases, in the city of Mashhad in Iran, to identify the sustainability of wastewater treatment plants (WWTPs), focusing on eco-efficiency based on LCA and energy, and to estimate the impacts associated with the sludge or effluents produced. To determine the technical performance and eco-efficiency index of WWTPs, two parameters were considered: the value of the organic load and the nutrients removed. The results showed differences between the two studies, with the removal of 1 kg of organic load in one of the analyses increasing its added value. Eco-efficiency as a process of combining analyses made it possible to identify which WWTP was the most sustainable in both economic and environmental terms (Alizadeh et al., 2020).

### 3.2.4 Life Cycle Assessment as a guide for public policies for municipal solid waste

Energy policies are designed to develop and manage available energy resources effectively. In the context of energy generated from MSW, LCA can significantly contribute to this process by assessing the environmental impact at all stages of the transformation cycle (Sridhar et al., 2021). This comprehensive approach considers environmental implications at all stages of the life cycle, from resource extraction to disposal (Nubi, Morse & Murphy, 2022). An energy policy that prioritizes waste management is increasingly significant in today's global context, where MSW production is increasing (Dai & Taghavi, 2021).

When analyzing the issue of food waste and the consequent production of MSW in India, Sridhar et al. (2021) emphasize the importance of well-defined public policies for better decision-making. Furthermore, according to Dai and Taghavi (2021), proper MSW management not only helps reduce waste production but also creates opportunities to establish markets for recycled materials, generate jobs, and improve energy recovery. Thus, energy policies that integrate waste management strategies can lead to more sustainable development by addressing environmental and economic challenges.

## 4 Conclusion

This study aimed to review the research trends on life cycle assessment (LCA), life cycle cost (LCC), and levelized cost of energy (LCOE) in the context of energy recovery from MSW through bibliometric

and systematic analysis, and to explore the relationship of these concepts with eco-efficiency within the framework of public policies.

In the bibliometric analysis, articles were examined based on co-authorship between countries, the co-occurrence of authors' keywords, and the most relevant sources. The analysis revealed that China leads in the number of publications, followed by the USA and Italy. In terms of international collaborations, the United Kingdom has the most partnerships with other countries. However, the USA stands out with single collaborations, while China has numerous multi-country collaborations.

The analysis of the most frequently used keywords by authors showed that the key terms are "life cycle assessment," "life cycle analysis," and "energy recovery." This suggests that research on energy recovery from MSW is focused on both macro-level analyses, which assess the overall environmental impacts, and micro-level analyses, which examine specific processes of waste treatment and recovery.

The systematic review of ten selected articles aimed to identify how these studies address LCA, to identify an integrated approach the analyses, that includes LCA, LCC, and LCOE. The results highlight the need for more studies focused on the eco-efficiency of energy recovery from waste and for integrating these concepts into public energy policies based on MSW. The findings suggest that while LCA is an important tool for measuring environmental impacts, it must be complemented by specific analyses such as cost and energy consumption to provide a comprehensive assessment that accurately reflects all impacts throughout the MSW energy generation process.

The study hopes to contribute to new research by broadening the discussion on the application of LCA in MSW, as this topic is already widely debated. However, there are still areas that require further attention, including the issue of eco-efficiency. A limitation of this research is that it relied on data from a single source (Web of Science). For future work, it is suggested that data from other databases be included, increasing the scope of the analyses.

#### Acknowledgments

The authors express very gratitude for the financial assistance received from CEFET and the Brazilian National Council for Scientific and Technological Development (CNPq), grant number 406789/2018-5, and was financed in part by the Brazilian Coordination for the Improvement of Higher Education Personnel (CAPES) - Finance Code 001.

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# Comparative Analysis of Low-Carbon Hydrogen Industrial Plants, Based on Environmental Impact Studies

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## Abstract

The energy transition is a gradual process of changing non-renewable sources to renewable ones to slow climate change, impacting the entire planet. Because of this, several countries have adopted wind and solar energy in their electricity grids. In addition, hydrogen is another growing resource that can generate electrical and thermal energy, storage, and mobility, helping decarbonization. Hydrogen can be obtained differently, but this study will focus on production from the alkaline electrolysis process using renewable sources. The proposal compares four low-carbon hydrogen and ammonia plants installed in the Port of Pecém in Ceará. In the analysis, the production capacity of each system will be verified, including the occupied area, water consumption, and electrical energy. Finally, it was concluded that Casa dos Ventos is more efficient than the others in producing renewable hydrogen and low-carbon ammonia per occupied area. At the same time, Fortescue would have the best water and electricity consumption performance.

## 1 Introduction

The Brazilian electricity matrix comprises more than 80% renewable sources, one of the cleanest on the planet (EPE, 2024). Furthermore, Brazil is currently well-positioned in the ranking of the best places to invest in new industrial hubs for low-carbon products, given the added value of this matrix.

Investing in low-carbon products allows Brazil to comply with the agreements signed at the United Nations Climate Change Conference (COP) and in the energy transition process, enabling the decarbonization of the production chain. Among the products with such potential are renewable hydrogen and its derivatives, such as low-carbon ammonia (Ge et al., 2024). Hydrogen can be produced in different ways; in the electrolysis process, it is possible to adopt renewable energy resources in production. Hydrogen and its derivatives can be used as fuel, transportation, and energy storage (Ishaq et al., 2022).

According to H2 Brasil (2023), Brazil already has 42 renewable hydrogen and derivatives plant projects in operation, construction, and/or licensing. This creates expectations for the domestic and foreign markets. However, the possibility of building new industrial facilities must comply with the country's laws and regulations. Brazilian laws require studies to be carried out to analyze the environmental feasibility of projects that may cause environmental degradation or pollution.

Environmental Impact Studies (EIA) and Environmental Impact Reports (RIMA) are documents that are part of the country's legislative process and must be submitted to the Brazilian Institute of the Environment and Renewable Resources (IBAMA), the regulatory body, and to society to verify the project's feasibility (PNLA, 2024).

Based on the information provided in the EIAs of each plant, it is possible to assess the environmental impact and, in addition, the performance of the facilities. Thus, this study proposed to compare the EIA project of four low-carbon hydrogen and ammonia production plants that use the same hydrogen generation technique, alkaline electrolysis. Furthermore, the plants installed in the same region were selected in the port of Pecém/CE, a place known for generating photovoltaic or wind turbine electricity.

Also, within this context, the location of these plants in Ceará is strategic due to its geolocation, which facilitates the flow of production, storage, and distribution activities of products, whether for internal consumption with transportation via highways or pipelines or external consumption with maritime transportation. It is essential to mention that some of the analyzed projects agreed to flow the product to the port of Rotterdam in the Netherlands (FORTECUE, 2023).

In the comparative analysis between the four plants, each system's production capacity of inputs will be verified concerning the occupied area, water, and electricity consumption. Finally, the performance of each renewable hydrogen and low-carbon ammonia plant will be analyzed, as well as the others, to determine which will have the best efficiency for using available natural resources.

## 2 Methodology

This paper aims to perform a comparative analysis based on data from the Environmental Impact Studies provided by each company. Initially, the companies that had applied for an environmental license with the Brazilian Institute of the Environment and Renewable Resources (IBAMA) were verified, and an analysis of possible projects that could be compared was performed. The plant selection criteria followed the following sequence: location, type of renewable hydrogen and low-carbon ammonia production process, data on the area occupied, and water and electricity consumption.

Within this context, four EIAs were identified that met the selection criteria, which were Indústria Brasil Fortescue Sustainable Industries, Casa dos Ventos e Energias Renováveis, AES Brasil Energia, and Qair H2 Brasil. With this, other information on each renewable hydrogen and derivatives production plant was verified, the details of which are described in the next section.

After collecting the data, the performance analyses considered that all of them would already be fully operational, i.e., a projection for 2035 when all of them would have fully operational systems.

In the comparison, the proposal was to standardize the data. Thus, the sum of the final products generated by the plant was considered, i.e., the sum of all hydrogen and ammonia generated by each project throughout the year (tons/year) and then divided by the natural resource, which was occupied area, water consumption, and electricity consumption. In Equations 1, 2, and 3, it is possible to verify the respective proposed relationships.

$$X = \frac{H_2 + Ammonia}{Area} \quad \left[ \frac{ton}{year \cdot ha} \right] \quad (1)$$

$$Y = \frac{H_2 + Ammonia}{Water} \quad [-] \quad (2)$$

$$Z = \frac{H_2 + Ammonia}{Electrical} \quad \left[ \frac{ton}{MW} \right] \quad (3)$$

Equations 1, 2, and 3, graphs were created, and the plants with the best efficiency, about the other companies, for each available natural resource were evaluated. Below are some characteristics of electrolysis processes and a description of each renewable hydrogen and low-carbon ammonia production plant.

## 2.1 Electrolysis Technologies

Industrial hydrogen plants' main component is the electrolyte, which can be of the following types: solid oxide, alkaline, proton exchange membrane, and anion exchange membrane. The different technologies are discussed below.

1. Solid Oxide Electrolyzer Cell (SOEC) technology has been the focus of development efforts for high-temperature electrolysis. This technology is less mature than polymer electrolyzers (PEM) or alkaline electrolyzers. Its low cell power and high operating temperature, which in turn requires more auxiliary equipment to operate the electrolyzer, are widely seen as the main disadvantages of SOEC technology. These systems are considered to have a shorter operating life due to thermal stress. Since SOEC manufacturers agree on a shorter cell life of their technology compared to alkaline and PEM technologies, they design their cell modules to be easily accessible in case of failure. SOEC uses O<sub>2</sub> or H<sup>+</sup> conduction and has a solid ceramic membrane, having an operating temperature of 500°C and 900°C (CLEAN TASK FORCE, 2023).
2. In the Alkaline Electrolyzer, the chemical reaction occurs between two electrodes immersed in a water solution, using sodium hydroxide as the electrolyte. At the cathode, hydroxide (OH<sup>-</sup>) and hydrogen (H<sub>2</sub>) molecules are formed from water molecules and renewable energy's current application. Hydroxyl ions migrate through the membrane to react at the anode to obtain oxygen (O<sub>2</sub>) and water. Hydrogen gas is produced close to atmospheric conditions when operating with an alkaline electrolyte. Currently, the Alkaline Electrolyzer technology is more mature, which is why it is the most common technology on the market and has a lower investment cost than other technologies. However, the regeneration of the liquid electrolyte requires larger electrolytic modules, thus increasing the physical structures. The alkaline electrolyzer has an operating temperature of 65°C and 95°C (FORTEESCUE, 2023).
3. The PEM electrolyze is a technology that allows operation with higher levels of current density and higher levels of hydrogen (H<sub>2</sub>) purity (5.0 = 99.999) in a smaller physical space. The types of membrane and use of platinum group metals in the electrode, due to the acidic environment associated with the electrolyte, its short useful life, estimated at around half the alkaline time, and higher energy consumption for hydrogen (H<sub>2</sub>) production. The PEM electrolyze has an operating temperature of 50°C and 80°C (FORTEESCUE, 2023).
4. In the Anion Exchange Membrane (AEM), these are ionomeric materials used in alkaline electrochemical devices, such as electrolyze. In AEM, demineralized water enters through the cathode, results in H<sub>2</sub>, and passes through an FFA membrane, through OH<sup>-</sup>, which passes

through an anode, which can be made of Nickel, Copper, or Iron. The AEM electrolyze at an operating temperature of 40°C and 80°C (CLEAN TASK FORCE, 2023).

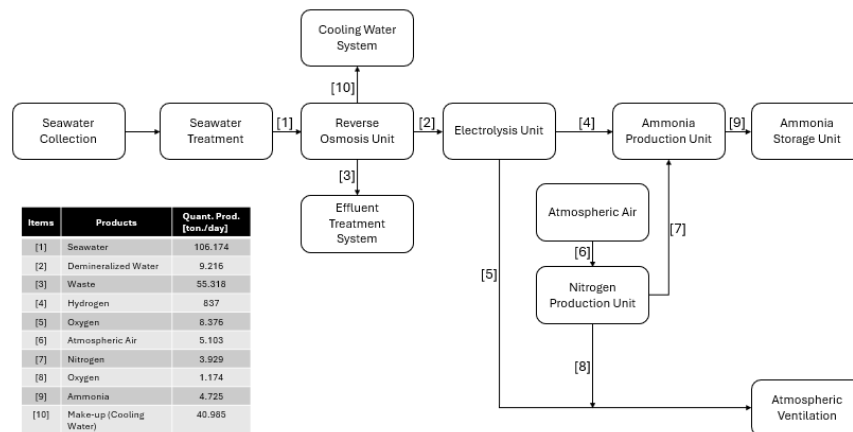
## 2.2 Description of Selected Industrial Plants

In this study, we evaluated low-carbon renewable hydrogen and ammonia plants. These plants align with the Laws and society's desire for more significant concern about pollution and, consequently, with the strategies needed to mitigate climate change.

For the hydrogen plant to function fully, in addition to the electrolyte depending on injected electrical energy, there is another critical input: treated water. This can be obtained in different ways, such as surface water, which is obtained from rivers, lakes, and canals; groundwater, from groundwater; reused (industrial) water; or seawater.

The characteristics of each industrial plant proposed for the port of Pecém in Ceará are presented below, using environmental impact studies as a database.

1. Fortescue Sustainable Industries Ltda. The Environmental Impact Study (EIA) of the FORTESCUE industrial plant was approved, and it is to be installed in the Pecém Industrial and Port Complex in the municipalities of Caucaia and São Gonçalo do Amarante. This plant is in the Port of Pecém, 35 km from Fortaleza, in the State of Ceará. According to the Gantt Chart, it is expected to be completed in 48 months, with a three-phase construction schedule and an estimated area of 135 hectares. At the end of the three phases of the alkaline electrolyze plant, it will be able to supply 1,725 thousand tons per year of renewable ammonia and 392 thousand tons per year of renewable hydrogen, with an electrical energy consumption of 25,200 MW. This plant uses seawater to feed the alkaline electrolyze, with 3,363,840 tons per year of demineralized water (FORTESCUE, 2023). Figure 1 shows the block diagram of the Fortescue Plant.



**Figure 1:** Fortescue Industrial Plant Block Diagram (Source: adapted from Fortescue Brazil EIA).

The CHESF System feeds the substation area through 230 kV transmission lines to the substations involved. The energy generated can be of two types: by the Uruquê Photovoltaic Park, with 25,200 MW, to produce ammonia and hydrogen, Jaguaratama Municipality and Umari Municipality and by the Camocim Offshore Wind Farm, with 1,200 MW, for

administrative use, and is in the Camocim Municipality, in Ceará (FORTESCUE, 2023; FORTESCUE, 2024).

2. Casa dos Ventos e Energias Renováveis S.A. The company presented its project to the Pecém Industrial and Port Complex (CIPP) in Caucaia and São Gonçalo do Amarante municipalities. This presentation showed the Renewable Hydrogen (H<sub>2</sub>V) production unit, with storage and transportation in the form of Renewable Ammonia (NH<sub>3</sub>). The production area of this renewable hydrogen plant is 60 hectares. A four-phase schedule for the construction of the alkaline electrolyze plant will be able to supply 378 thousand tons per year of renewable hydrogen, simultaneously with 2,130 thousand tons per year of renewable ammonia. This will have a reuse water consumption of 10,500 tons per year and will be able to receive treatment at the Reuse Water Production Station (EPAR). The electricity consumption is 33,600 MW. It will have 500 kV Transmission Lines SE PECÉM II x SE GHP (MRS Ambiental, 2023).
3. AES Brasil Energia S.A. The hydrogen and renewable ammonia production plant will be installed in sector II of the Export Processing Zone (ZPE) near the Pecém Port Terminal, with an EIA presented in March 2024. The production area of this plant will be 80 hectares. Its production capacity will be 800 thousand tons of renewable ammonia per year, with a consumption of 142 thousand tons of renewable hydrogen per year, and it will take 36 months to be installed. AES forecasts an increase in the production of 1,200 thousand tons of renewable ammonia per year. The flow of demineralized water for production will be 1,787 thousand tons per year. AES's option has a 500 kV transmission line and substation, estimated at 16,080 MW (Pecém, 2024; HL Soluções, 2023).
4. QAIR H<sub>2</sub> Brasil S.A. The EIA for the project called H<sub>2</sub>FRATERNITÉ PROJECT, to be installed in the Export Processing Zone (EPZ, Sector IV) of the Pecém Industrial and Port Complex (PIPC), in the municipality of São Gonçalo do Amarante State of Ceará. The production plant will be installed in an area of 35 hectares. It will be responsible for fifty-six alkaline electrolysis cells and will produce 43 thousand tons of renewable hydrogen per year to serve the national market. Water sources will be used from underground wells, which will be 784 thousand tons per year. These must be purified, and there will be a water demand in the demineralized water plant of 574 thousand tons per year. A consultation will be carried out with the São Francisco Hydroelectric Company – CHESF, to attest to the physical feasibility of connecting the H<sub>2</sub>FRATERNITÉ PROJECT through the 500 kV LT SE Pecém II - SE H<sub>2</sub>Fraternité on the 230 kV bus of the Pecém II Substation (SE), estimated at 3,360 MW (ENERGO, 2024; AES, 2024).

Table 1 presents data collected from each renewable hydrogen and ammonia production plant: construction time, built area, construction phases, water consumption, ammonia and hydrogen production, electricity consumption, and consumption voltage.

Characteristics of the Hydrogen Plant	<b>Fortescue Sustainable Industries</b> [3]	Casa dos Ventos [5]	AES do Brazil [7]	QAIR H <sub>2</sub> Brazil [9]
Construction time [months]	48	48	60	24
Building area [ha]	135	60	80	35
Plant phases [-]	03	04	02	01
Treated water [ton/year]	3.364 mil	10.500 mil	1.787 mil	574 mil
Renewable ammonia [ton/year]	1.725 mil	2.130 mil	800 mil	NA
Renewable hydrogen [ton/year]	306 mil	378 mil	142 mil	43 mil
Electrolyze electrical [MW/year]	25.200	33.600	16.080	3.360
Supply voltage [kV]	230	500	500	230

**Table 1:** Data from hydrogen plants and derivatives based on EIA.

Table 1 shows that the construction time for Fortescue and Casa dos Ventos is similar, at 48 months, while AES will need more time for full implementation (60 months) despite having only two phases of production expansion. QAIR will implement the project more quickly, with only 24 months of construction and one phase. Despite the differences in time and phases, the comparative efficiency analysis will consider that all plants will be fully operational.

Another highlight in Table 1 is water consumption since the Casa dos Ventos plant is the largest consumer. There may be some change after the EIA analysis or when the plant is implemented. The main issue is the ratio of hydrogen and ammonia production to water demand, which has a much higher proportion. This is also the case with the QAIR plant.

A comparative analysis will then be made between the different plants to determine which project efficiently uses natural resources.

### 3 Results and Discussion

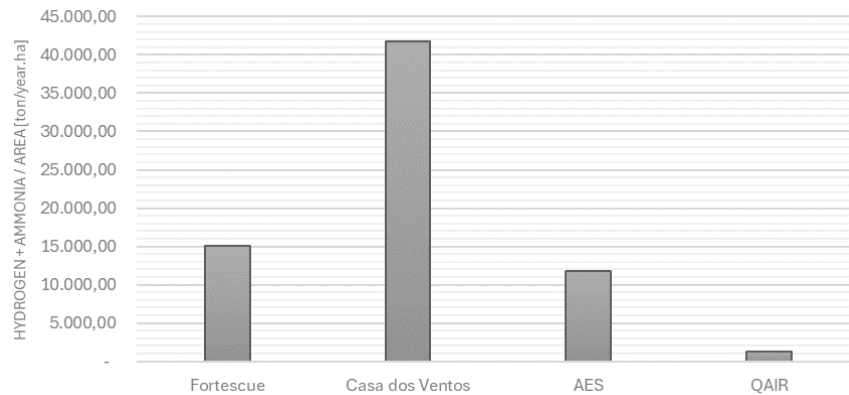
The four renewable hydrogen and low-carbon derivatives plants will begin operating in 2027 but will only be fully operational in 2035 (FORTESCUE, 2023). The analysis will consider that all projects are fully operational, delivering the total products reported in the EIA.

The production of low-carbon hydrogen and ammonia are the main objectives of these plants. That said, the production of each one stands out, starting with Fortescue, which will produce 306 thousand tons of renewable hydrogen and 1,725 thousand tons of renewable ammonia in an area of approximately

135 hectares (FORTESCUE, 2023). Casa dos Ventos will be able to produce 378 thousand tons of renewable hydrogen and 2,130 thousand tons of renewable ammonia in 60 hectares (MRS Ambiental, 2023). In this context, AES Brasil will produce 142 thousand tons per year of renewable hydrogen and 1,200 thousand tons per year of renewable ammonia in an area of 80 hectares (HL Soluções, 2024). Meanwhile, Qair H2 Brasil will produce 43 thousand tons of renewable hydrogen per year on 35 hectares (ENERGO, 2024).

Figure 2 shows the relationship between the production of hydrogen and ammonia and the area occupied by each plant, and it is clear that Casa dos Ventos has the best relationship, as it presents values well below.

Figure 2 shows the relationship between hydrogen and ammonia production and the area occupied by each plant. Thus, Casa dos Ventos has the best relationship, presenting values well above the second-placed plant, Fortescue. This demonstrates that the compaction capacity of the hydrogen and ammonia generation system at Casa dos Ventos far exceeds the others and is the EIA project with the best space occupation efficiency. The Fortescue and AES plants were very close in terms of the use of this natural resource, while QAIR has the lowest efficiency in this regard.



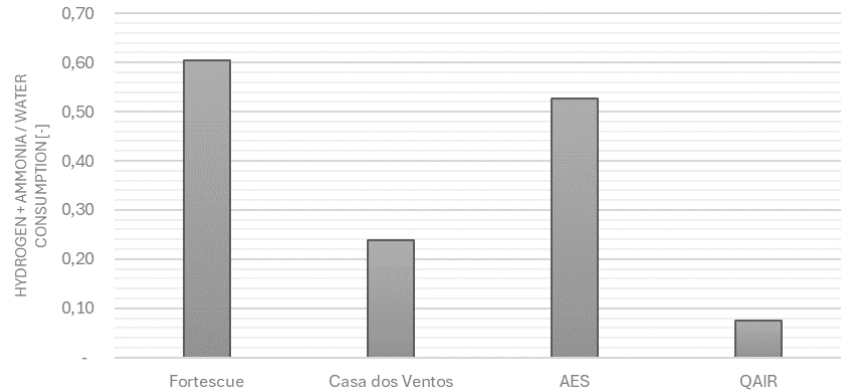
**Figure 2:** Ratio between the production of inputs and the area occupied by each proposed plant.

Regarding water consumption, Fortescue will collect raw ocean water, approximately 38,753,510 tons per year. After treatment, it will have demineralized and deionized water, which will undergo reverse osmosis, totaling 3,363,840 tons per year (FORTESCUE, 2023); as for Casa dos Ventos, the desalinated water will come from reused water approximately 10,500,000 tons per year. However, there is great concern regarding Section-5, which is located between the Gavião Reservoir and Pecém and has a maximum flow of 22 m<sup>3</sup>/s, of which 19 m<sup>3</sup>/s are intended to supply the Fortaleza region, including the Pecém Industrial and Port Complex. If there is any impediment to its use, Casa dos Ventos will use saline groundwater or another type of raw water until reused water is available (MRS Ambiental, 2023).

The “AES Pecém Green Ammonia Plant” project consists of filtered raw water, which will be 9,040 thousand tons per year. In addition, the consumption of demineralized water for the production of ammonia, which will use the Haber Bosch process with alkaline water in electrolysis, will be 1,787 thousand tons per year (HL Soluções, 2024).

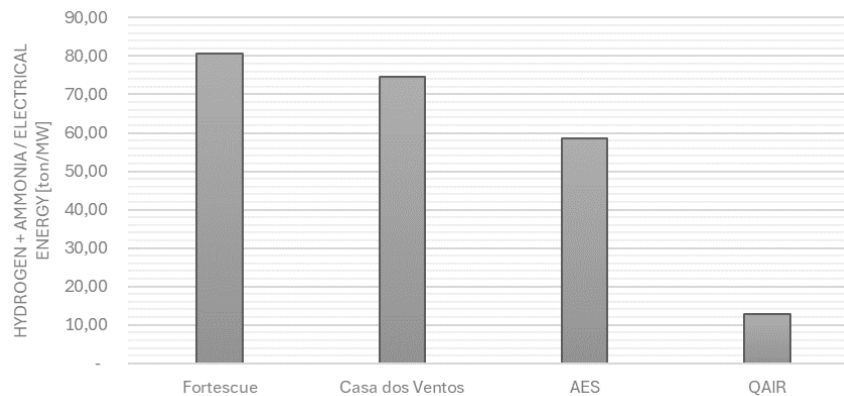
The Qair H2 will have a raw water treatment capacity of 574 thousand tons per year. According to the EIA, the plant can install a pipeline that will connect the reused water plant to complete the groundwater collection flow. Alternatives can be implemented, such as seawater desalination (ENERGO, 2024).

Figure 3 shows the relationship between the four selected plants' hydrogen and ammonia production and water consumption. Based on the data presented, it is possible to state that Fortescue is consuming water more efficiently since it can produce more with less water. AES also has excellent results and is close to Fortescue, with a difference of approximately 14.5%. Casa dos Ventos and QAIR have efficiencies much lower than Fortescue, with differences of 152.7% and 705.9%, respectively.



**Figure 3:** Ratio between the production of inputs and the water consumption of each proposal.

In Figure 4, it is possible to follow the projection of hydrogen and ammonia production per electrical energy consumption in each selected plant. In the case of Fortescue, it can be seen that for every 1 MW, 80.6 tons of products will be produced, while Casa dos Ventos will produce 74.64 tons for 1 MW. Fortescue will be around 8% more efficient than Casa dos Ventos. Compared with AES and QAIR, this percentage will increase to 37.6% and 530%. Given this, Fortescue has a plant that can use less electrical energy than the others to produce the same amount of hydrogen and ammonia.



**Figure 4:** Ratio between the production of inputs and the electrical energy consumption for each proposal.

After these comparative analyses, it was possible to verify that the data provided by the Environmental Impact Studies (EIA) are limited, and some points, such as the equipment used in each

stage of production, the traceability processes, logistics, etc., could be improved. However, the data allowed a preliminary analysis of how the selected hydrogen and ammonia plants will behave when fully operational.

## 4 Conclusion

Brazil holds a privileged position in the ranking of countries with a predominantly renewable energy matrix, which allows the production of products with a lower carbon content compared to other countries whose matrix has a higher proportion of non-renewable sources.

Within this context, the country could assume a privileged position in generating low-carbon hydrogen and ammonia, which can allow for the decarbonization of the production chain and help advance the energy transition. The option to develop renewable hydrogen and low-carbon ammonia HUBs in Brazil is also due to some factors, which are proximity to ports for export, the possibility of installing hydrogen and ammonia pipelines to distribute them throughout the country, and the intention to increase the electricity matrix with renewable sources.

Regarding the four Environmental Impact Studies of hydrogen and ammonia plants selected, all intend to generate products with low carbon generation, with priority given to using electricity from renewable sources to supply the energy consumption of alkaline electrolytes.

Still, regarding the EIAs of the industrial plants, when observing the efficiencies, only with the data presented, it was concluded that Casa dos Ventos is more efficient than the others in the production of hydrogen and ammonia per occupied area. In terms of water and electricity consumption, Fortescue performs better. However, regardless of efficiency, all will positively impact the port of Pecém/CE, bringing investment and development to the region.

In the future, it is expected to conduct new studies with other low-carbon hydrogen and ammonia production plants to be installed in the country and, in addition, to seek a partnership with companies to have sufficient data to help them select equipment that may be more efficient in terms of consumption of natural resources.

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# Biomass feeding systems – are we ready to run cellulosic ethanol plants?

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## Abstract

The constant ups and downs in recent cellulosic ethanol plants' operational performance still challenge companies and researchers. Although new technological developments to convert lignocellulosic biomass to ethanol made the construction of pioneer industrial facilities viable over the last years, their stable and continuous operation has not been achieved yet. Besides issues concerning conversion processes, pioneers' plants faced, after their start-up, several problems in biomass feeding equipment that seemed to have been unexpected by both plant operators and their equipment suppliers. To check if these problems happened due to the lack of specific technological development for equipment handling biomass, this study carried out broad patent research on more than 600,000 patents applied worldwide. Its results detected just a tiny number of patents on equipment design for lignocellulosic biomass. None of them dealing specifically with biomass types used in the pioneer cellulosic ethanol production plants. A potential lack of technological development may have been one of the causes for their relatively low operational performance. This research was developed through new search strategies to be used in big databases and contributes to the identification of the next technological challenges to be faced by production plants using biomass as feedstock on an industrial scale.

# 1 Introduction

Since 1920, after displacing coal and assuming the position of the primary source of energy generation, oil has been consolidating itself as the leading world energy source. But not only energy, since then oil has also become the primary source to produce other chemicals that, together with fossil fuels, structured the 20th-century economy and were fundamental to the economy and the technological development that would follow (Bennett & Pearson, 2009). This leading position of oil remained uncontested for 50 years until it was shaken by successive crises that caused large oil price fluctuations and aroused interest in the search for alternative energy sources (Calise et al., 2019; Philp, 2018; Rosales-Calderon & Arantes, 2019; Viswanathan, 2015).

Even after 2008, with the drop in oil prices, the pressure to replace fossil fuels with renewable sources continued to reduce the carbon emission load in the atmosphere. Among the various renewable sources that stood out in the research's development since early in the 2000s is biomass, which has been considered an essential competitor with petroleum as a source to produce automotive fuels (Cherubini, 2010; Rosales-Calderon & Arantes, 2019).

As the most widely used biofuel in the world, bioethanol was the natural candidate to be the main competitor of fossil fuels. Its production had been made from raw materials based on sugar and starch (mainly sugarcane and corn) with a production volume still incapable of meeting global fuel needs. One of the alternatives was developing innovations to enable bioethanol production also from lignocellulosic biomass (Cherubini, 2010; Gustafsson et al., 2015; Rosales-Calderon & Arantes, 2019; Soccol, Carlos Ricardo; Brar, Satinder Krau; Fauds, 2016). Ethanol produced from starch and sugar is called first-generation ethanol (1GE), while the one made from lignocellulosic biomass is known as cellulosic ethanol or second-generation ethanol (2GE).

Over the past 50 years, research and discussions about lignocellulosic biomass were concentrated on conversion processes (pre-treatment, enzymatic hydrolysis, and fermentation) to produce biofuels (Akhtar et al., 2016; Calderon & Arantes, 2019; E4tech, 2015; García et al., 2014; Gustafsson et al., 2015; Kang et al., 2015; Nogué, Violeta Sánchez; Karhumaa, 2014; Tiwari et al., 2015; Vimmerstedt, Laura J; Warner, Ethan S; Stright, 2016). Such efforts resulted in the implementation of the pioneer's 2GE production plants between 2013 and 2015. Until 2GE plants start-ups, studies dealing with biomass as industrial feedstock concentrated their research and discussions on conversion processes: pre-treatment, enzymatic hydrolysis, and fermentation (Calderon & Arantes, 2019; Energy, 2016a; Viswanathan, 2015). However, the difficulties faced by 2GE plants suggest that besides the expected issues related to the conversion processes, other challenges must also be faced to run continuously new plants using biomass as feedstock on an industrial scale.

The question, around which, this research is developed is whether there are technological developments for handling the biomass types used in these pioneer plants or if it is one of the next technological challenges to be faced. The next sections present a brief description of the 2G ethanol case, the methodology used in the patents search, followed by its results, discussions, and conclusions.

## 2 Methodology

Technology foresight is a process that analyzes the long-term future in science & technology to identify strategic areas of research and emerging technologies. It could make it possible to understand the forces that can shape the future and be considered to formulate policies, planning, and decision-making. Technology foresight is not just about evaluating novelties, but also identifying the level of

technological maturity of the invention or innovation (Technology Readiness Level - TRL): to identify publications about the technology in the form of abstracts (TRL1-2) or indexed papers (TRL3), when searching for bibliographic information. It is also helpful to check if there are advances in technology development in the form of pilots (TRL4-6) or demonstration-scale (TRL7-8), or even commercial scale (TRL9). If there are the same technologies that are already being commercialized on the market, then the technology is already in TRL9. The simplest form of technology foresight is the search for a priority through patents (Antunes, Adelaide Maria de Souza; Parreiras, Viviane Masseran Antunes; Quintela, M. Cristina; Ribeiro, 2018).

Research-based on patent search grows every year (Madani & Weber, 2016). Patent analysis has been considered a very efficient method to investigate the history and state of the art in a technology area (Antunes, Adelaide Maria de Souza; Parreiras, Viviane Masseran Antunes; Quintela, M. Cristina; Ribeiro, 2018; Park et al., 2018). About 70% of innovative companies use patent information in their innovation processes (European Patent Office, 2017).

This research aims to find and analyze patent documents (PD) containing designs of solid handling equipment sized for the different types of lignocellulosic biomass used in innovative 2GE plants. The strategy defined for research and selection of PD is through keywords (WIPO, 2019) and follows two different paths, as shown in Fig. 1.

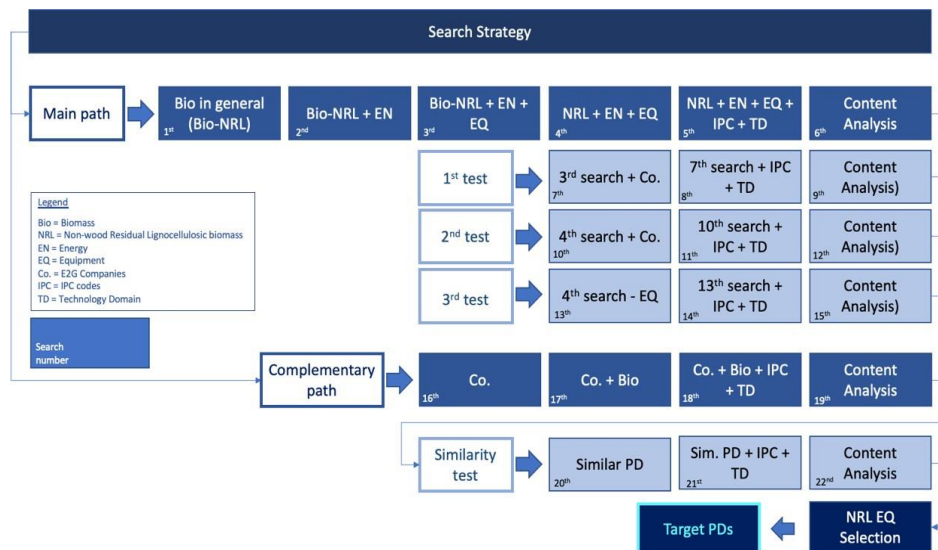


Figure 1: Search Strategy

The Main path starts from the keyword 'Biomass' submitted to three tests and a Complementary path that begins from patents applied by companies linked to the production of 2GE. The results from the two paths are subjected to a last 'similarity test' that searches for PD similar to the final selection to search of patents eventually excluded from both paths. All these steps are detailed below.

The keywords used are: BIOMASS (for biomass in general); STRAW, STOVER, BAGASSE, CORN, CANE, WHEAT and ARUNDO (for residual lignocellulosic biomass); 'CANE STRAW', 'CORN STOVER', 'SUGARCANE BAGASSE', 'WHEAT STRAW' and ARUNDO (for the specific types of biomass used in 2GE plants); FUEL \*, BIOFUEL \*, ENERG \*, BIOENERG \*, ETHANOL, BIOETHANOL (to identify patents addressed to the energy or fuel sectors) and, HAND \*, TRANSPORT \*, SCREW \*, CONVEY \*, MILL \*, GRIND \*, CRUSH \*, SIEV \* (to identify patents including typical solid handling equipment). The keywords were searched in "title", "abstract", "claim" and "object of invention", and considered PDs alive (granted and pending) and dead (lapsed, revoked, expired), since both categories contain valid technological for this study (INPI, 2016).

Two additional classificatory filters (available by Orbit) are used in the PD selected in the previous steps: International Patent Classification and Technology Domains.

To clearly define the type of raw material included in each patent, "Non-wood Residual Lignocellulosic biomasses" are generally called NRL. The "Specific types of Non-wood Residual Lignocellulosic" biomass used in pioneer 2GE plants are called SNRL. For example, sugar cane straw or wheat straw or sugarcane bagasse should be considered SNRL, while straw or bagasse treated generically in patents are deemed to be NRL.

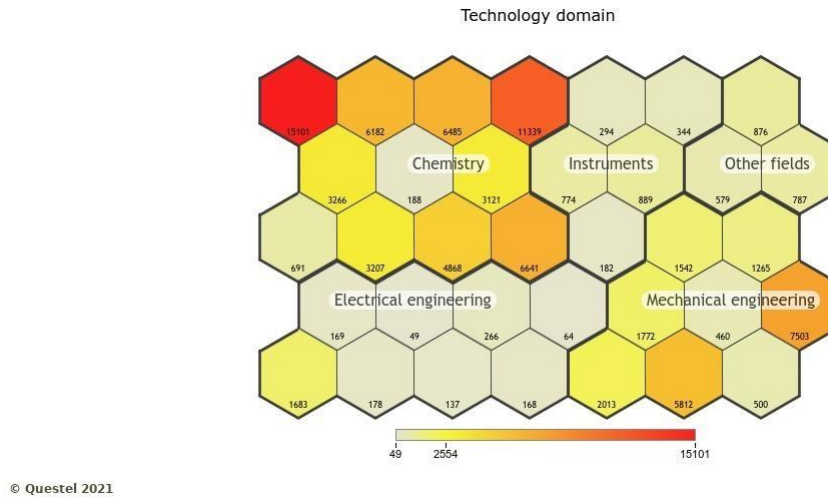
Three tests are applied in the main path to verify its effectiveness: the first two tests include 48 companies related to the 2GE production to search for PD not found through the keywords used at the beginning of the searches. Companies' names were selected on searches in newspapers, business magazines, and journals. The third test checks whether any PD that deals with any other type of solid handling equipment not listed in the corresponding filter would have been improperly excluded.

## 3 Results and Discussion

### 3.1 Search Strategy Results

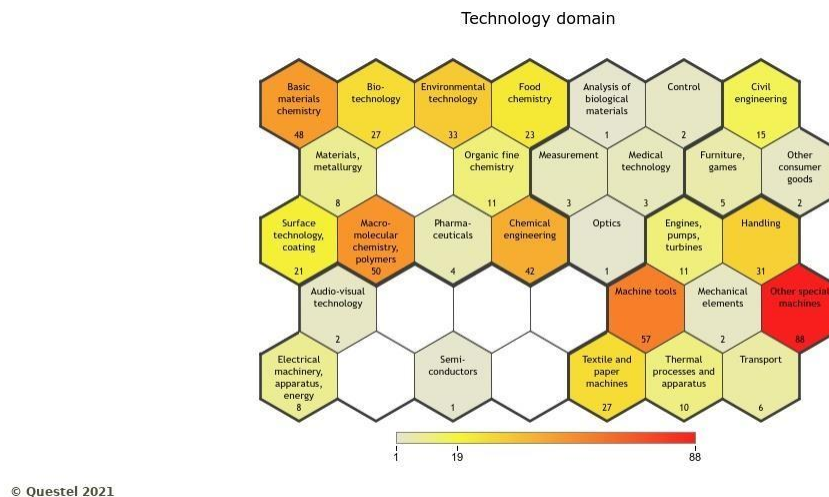
The Main path yielded, at first, 639,319 PDs on biomass in general regardless of its intended final use – industrial use, agriculture, or even urban waste. This total also includes patents dealing with wood, whose development for the pulp & paper industry is relatively consolidated, and many biomass types used in other fields.

Upon applying filters for energy/fuel industries and solids-handling equipment, the total number of findings was reduced to 58,198 PDs: less than 10% of all biomass patents initially identified with the keyword 'biomass'. Most of them concentrated in the field of Chemistry (see Fig. 2).



**Figure 2:** Technology Domain Family Fields / 3<sup>rd</sup> search – Main path

After removing the keyword “biomass” and keeping the keywords identifying NRL biomass, the result was reduced to 5,640 PDs, indicating that, in the last 50 years, only 1% of all PDs on biomass were applied to target the specific types used in 2GE plants, connected to solids handling equipment. After TD and IPC filters, guiding the selection to Mechanical Engineering fields, only 171 PDs remained. Important to note that even using filters to guide de results to Mechanical Engineering, the number of PD in Chemistry remains very high (see Fig. 3). It may indicate that, as well as in scientific journals (Akhtar et al., 2016; E4tech, 2015; Energy, 2016a; García et al., 2014; Kang et al., 2015; Karimi, 2015; Nogué, Violeta Sánchez; Karhumaa, 2014), patent assignees also addressed their concerns on the conversion process, without emphasizing systems to handling and feeding raw materials.



**Figure 3:** Technology Domain Fields / 5<sup>th</sup> search – Main path

All these 171 PD's are dispersed among assignees. The company that has the largest number of PDs is the Chinese Xileco with 15. Another seven companies own two applications each. Not only does

China have the assignee with the highest number of patents, but it is also the origin country of the most significant number of assignees companies: of the first 30 companies in the ranking, 18 are Chinese.

However, this relatively large number of patents is not restricted to the case of cellulosic ethanol or the energy or alternative energy sector. According to the National Bureau of Statistics of China, patent applications, in general, increased from 25,000 to 300,000 between 2000 and 2010 in the country. An average annual growth rate of over 30%. This growth is due to R&D investments made in the country and mainly to a cumulative effect: amendments made in patent and private property legislations in China, patent subsidy programs initiated by Chinese provincial and foreign direct investment in patent applications. Important to empathize that experts claim that this sum of effects can also disproportionately stimulate the application of low-quality patents to receive the benefits (Albers et al., 2016; Chen & Zhang, 2019).

After qualitative content selection, only 4 of 171 PD's were classified as directly-related. The three tests applied on the main path identified 201 new PDs. However, upon content analysis, none of those were classified as directly-related, thus proving the main path's effectiveness.

The Complementary path, which started with PDs assigned by the 48 companies linked to the production of 2GE, yielded six new PDs classified as directly-related. All of those applied by Valmet, a major pulp & paper equipment manufacturer also working for 2GE. However, none of them was linked to energy/fuel production. That's, possibly, why they had not been selected on the Main path.

A Complementary path then added six PDs to the four Directly-related PDs of the Main path, increasing the total number of Directly-related PDs to ten (Handan Goldenlion Cotton Machinery, 2013; James Cunningham; Paul O'Reilly; Conor O'Kane; Vincent Mangematin, 2014; Shandong Shankuang Machinery, 2007; Urumqi Animal Husbandry Abundant Weiye Agricultural Machinery Manufacturing, 2015; Valmet; Metso Paper; Valtra, 2012; Valmet, 2013a, 2013b, 2014, 2017; Valmet Technologies; Metso Paper, 2001).

The Similarity test applied to these ten PDs did not identify any new patent, confirming the final number. Fig. 4 shows a summary of the results of all searches.

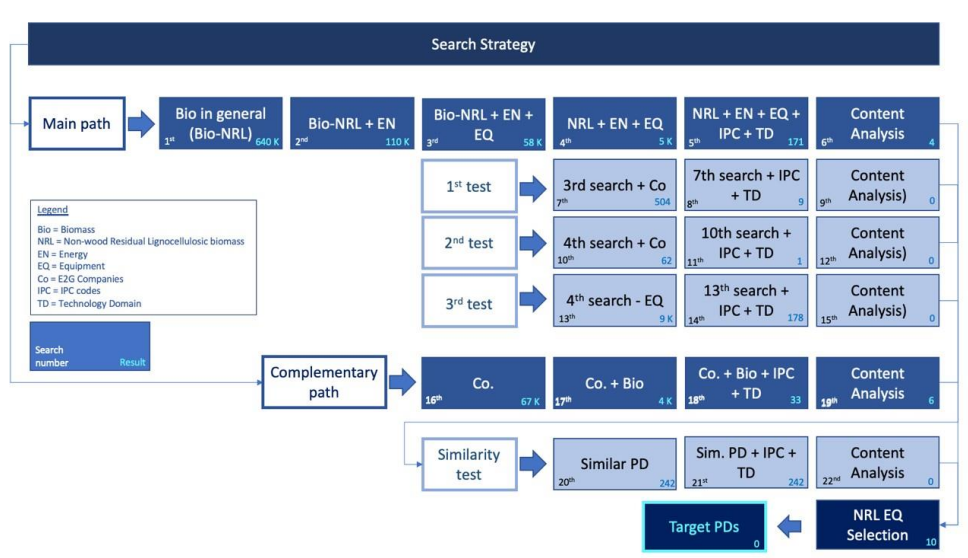
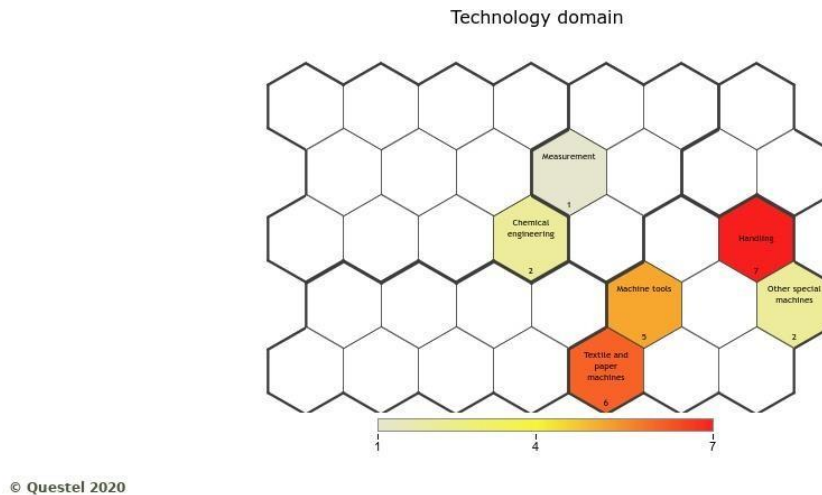


Figure 4: Search Strategy Result

### 3.2 Final Selection

Most of the final ten directly-related PDs are concentrated in the Mechanical Engineering field (see Fig. 5), indicating that the filters applied to the initial 687 thousand PDs (Main path + Complementary path) were effective in leading the results to this field.



**Figure 5:** Technology Domain Fields / NRL EQ selection

The evolution of PD application over time shows that nine of the ten PDs were applied from 2007 – a period of strong crisis and big raises in the oil price, with a small peak in 2013-2014, coinciding with another big financial crisis and with the beginning of the 2GE plants construction phases.

Most PDs were applied with priority in China (four) and Europe-EPO (four). The other two were applied in US. One applied by a University (in China) and the other nine by companies.

Valmet applied six out of the ten PDs – which was one of the suppliers of equipment and technology for some 2GE plants (Valmet; Metso Paper; Valtra, 2012; Valmet, 2013a, 2013b, 2014, 2017; Valmet Technologies; Metso Paper, 2001). Valmet is one of the biggest manufacturers of equipment and systems for solids-handling and is present mostly in the pulp & paper industry. Their PDs were about equipment design for handling 'non-wood' and 'lignocellulosic material' and were classified in more than one technology domain ('machine tools, handling, textiles' and 'paper machines'). For comparison's sake, Valmet applied a total of 5,805 patents in all fields during the same period covered by this research – among those, only six (0,1%) concern to object of study.

Metso and Andritz, other prominent manufacturers of equipment for the pulp & paper industry, applied, respectively, 4,335 and 2,568 PDs during the same period, indicating that they also use the patent application to guarantee the rights over their knowledge. None of them were found among the ten directed related PDs selected in this research.

None of the ten PD selected focused on equipment design to handle/feed with one of the specific biomass types used in the 2GE production (SLRN) – our Target PD. Besides the six on non-wood and lignocellulosic material, the other four were on residual material (straw, stalk) in general.

Research results also shows that, besides the low concentration of patents per company, companies also had a low collaboration rate in applied patents. Among the last ten PDs, only Valmet and Clariant applied patents in collaboration with other companies.

## 4 Conclusions

In summary, none of the ten patents selected from hundreds of thousands were on equipment design for specific types of lignocellulosic residual biomass. Despite showing some interest from companies, researchers and universities on the topic, the result answers that there is no specific knowledge patented to feed different types of lignocellulosic biomasses in industrial facilities.

The tiny number of directed-related patents found after the final selection or even the absence of target patents, by themselves, does not constitute evidence of the lack of technology development since such knowledge could also be an industrial or technology secret. However, this tiny number of PDs added to the difficulties faced by 2GE plants to operate continuously, can be strong indicator that such knowledge, if it exists, did not reach those plants or the TRL9 maturity.

The target on developing complex chemical and biochemical technologies capable of converting lignocellulosic biomass to bioenergy and biofuels may have muddied the need for developing new feeding systems: the high number of patents in the field of ‘chemistry’ can indicate it. Part of the difficulties in handling biomass faced by the cellulosic ethanol plants may have happened due to the belief that equipment suppliers already had technologies capable of solving the problems would be found. Since each biomass behaves in peculiar ways and lignocellulosic biomasses were only recently tested on an industrial scale, it is quite unlikely that even the most traditional equipment supplier had consistent experiences with those.

The main objective of raw materials feeding systems in production plants is to guarantee homogenous flows (Energy, 2016b) and, judging from the obtained results both in 2GE plants operation and in this research, no exceptional innovations that considered new types of biomass have been made.

After more than a century of having oil as its main feedstock, the fuel production industry has dedicated and specialized in converting crude oil into fuels and chemical specialties. Since oil is a liquid with relatively similar characteristics, handling and feeding raw material may have become a minor problem for this industry. However, in the shift from the oil-based economy to the biomass-based economy, this reality seems to have changed. It may be necessary to make a new effort in techniques for handling these peculiar materials that did not have millions of years to become almost uniform. Assuming that any lignocellulosic residual biomass can be handled or fed in the same way, may have been a trap into which 2GE pioneers fell and into which other projects linked to the production of biofuels may also fail.

One contribution of this paper is to present a new search methodology that manages to drive the research to the technology fields intended to be analyzed and that can be used in the search for patents that contain specific types of equipment designs. Another contribution is to reinforce the high importance of feedstock as a technology driver when using biomass on an industrial scale and suggest that technologies for biomass conversion are still not completely ready, since new types of equipment for handling and feeding biomass should be the next technical challenge to be faced by the 2GE production plants to run continuously and prove themselves ready for the next steps.

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