MODELING THE EXPANSION OF GENERATION OF OFFSHORE WIND ENERGY IN THE NORTHEAST: MAXIMIZING BENEFITS FOR BRAZIL

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MODELAGEM DA EXPANSÃO
DA GERAÇÃO DE
ENERGIA EÓLICA OFFSHORE
NO NORDESTE: MAXIMIZANDO
BENEFÍCIOS PARA O BRASIL

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MODELING THE EXPANSION OF GENERATION OF OFFSHORE WIND ENERGY IN THE NORTHEAST: MAXIMIZING BENEFITS FOR BRAZIL

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ABSTRACT

The aim of this study was to determine the contribution of offshore wind energy to the energy matrix in the Northeast of Brazil by integrating a utility maximization model for the expansion of generation from this source. To this end, we discussed wind energy systems, and more specifically the viability of an offshore system. As for the methodological aspects, this research can be defined as bibliographical and documentary, as well as being a case study. With regard to the type of analysis, the study took a qualitative and quantitative approach. The results obtained show that investment in offshore energy in Brazil can occur due to the fact that the offshore energy matrix can bring the following benefits: taking advantage of the country's natural potential, which has an extensive coastline for installing these parks; increasing the diversification of renewable energy sources and consequently increasing energy security for growing consumption centers, such as data centers and artificial intelligence, opening doors to this market; technological and industrial development, promoting technological innovation in renewable energy and boosting the production chain in this sector; as well as reducing GHG emissions and the use of non-renewable energy sources.However, this transition to a more electrified and sustainable system poses challenges for energy security, mainly due to the concentration of production of essential minerals in a few countries, leading to a scenario in which public policies must also be constantly adjusted to guarantee global energy security. In view of the above, this study proposes to compile relevant characteristics and variables, as well as proposing a validated model for offshore parks to determine the behavior of project costs based on their initial characteristics (Xi), through simulations of varying scenarios in the study area. Therefore, based on the results achieved, it can be seen that this study contributes to understanding the different panoramas associated with the expansion of offshore wind energy in the northeast region and in the country.

Keywords: wind energy; offshore energy; Northeast Brazil.

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LIST OF ABBREVIATIONS AND ACRONYMS

AAE	Strategic Environmental Assessment
ABEEÓLICA	Brazilian Association of Wind Energy and New Technologies
AEP	Annual Energy Production
IEA	International Energy Association
ANEEL	National Electric Energy Agency
ANP	National Agency of Petroleum, Natural Gas and Biofuels
AOE	Annual Operating Expenses
BEIS	Department for Business, Energy and Industrial Strategy
BNDES	National Bank for Economic and Social Development
AC	Alternating current transmission
CAES	Compressed Air Energy Storage
CAPEX	Capital Expenditure
CAPM	Capital Asset Pricing Model
DC	Direct current transmission
CCEE	Electric Energy Trading Chamber
CCGT	Center for Science in Management and Technology
CEOs	Offshore Wind Farms
CEPEL	Electric Energy Research Center
CfD	Contracts for Difference
CI	installed capacity
CO 2	Carbon Dioxide
CONAMA	National Environment Council
COP28	28th Conference of the Parties of the United Nations Framework Convention on Climate Change
COVID	Corona Virus Disease
LCOE	Levelized Cost of Production
CZMA	Coastal Zone Management
DIP	Prior Interference Statements
AEP	Annual Energy Produced
ECMWF	European Center for Medium Range Weather Forecasts
EEG	Renewable Energy Sources Act
EIA	Environmental Impact Study
EMBRAPA	Brazilian Agricultural Research Corporation
EPCI	Energy per Installed Capacity
EPE	Energy Research Company
ESS	Energy Storage Systems
USA	United States of America
FCA	Activity Characterization Form
FCFS	First Come First Served
FCP	Palmares Cultural Foundation
FDA	Cumulative Distribution Function

PDF	Probability Density Function
FUNAI	National Indian Foundation
FIT	Feed-in tariffs
GHG	Greenhouse Gases
LNG	Liquefied Natural Gas
GW	Gigawatt
GWEC	Global Wind Energy Council
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
IBAMA	Brazilian Institute of Environment and Renewable Natural Resources
IBGE	Brazilian Institute of Geography and Statistics
IEA	International Energy Agency
IPHAN	National Historic and Artistic Heritage Institute
IRENA	International Renewable Energy Agency
IRR	Internal Rate of Return
LCOE	Levelized Cost of Energy
LERs	Energy Reserve Auctions
LF	Leveling factor
LFAC	Low Frequency Alternating Current
LI	Installation License
LO	Operation License
LP	Prior License
MEA	Maximize Energy Access
MEJ	Justus Empirical
MEL	Lysen Empirical
MFPE	Standard Energy Factor
MG	Graph
MMA	Ministry of Environment
MME	Ministry of Mines and Energy
MMV	Maximum Likelihood Method
MMVM	Modified maximum likelihood method
OLS	Ordinary Least Squares
MS	Ministry of Health
MW	Megawatt
NCEP	National Centers for Environmental Prediction
NEPA	National Environmental Policy
NIMBY	Not in my backyard”
NPV	Net Present Value
NREL	Department of Energy's National Renewable Energy Laboratory
NZE	net zero emission
OCSA	Outer Continental Shelf
SDG	Sustainable Development Goals
O&M	Operation and Maintenance Model
OIE	Internal energy supply
NGOs	Non-governmental organizations
UN	United Nations Organization
OPEX	Operating Expenses
ORE	Offshore Renewable Energy
OWFLO	Offshore Wind Farm Layout Optimization

PDF	Probability Density Function
R&D	Research and Development
PIRATAS	National Buoy Program and Anchored Matrix Forecast and Research Project in the Tropical Atlantic
PL	Bill
PNE	National Energy Plan
PNMA	National Environmental Policy
PRO-WIND	Emergency Wind Energy Program
PRODEENE	Priority Program for the Development of Wind Energy in the Northeast
PROINFA	Incentive Program for Alternative Sources of Electric Energy
RAS	Simplified Environmental Report
REIDI	Special Incentive Regime for Infrastructure Development
RIMA	Environmental Impact Report
RNA	Rotor-Nacelle Assembly Model
RO	Renewables Obligations
RPS	Renewable Portfolio Standards
SIGA	ANEEL Generation Information System
SIN	National Interconnected System
SISNAMA	National Environment System
STEPS	Stated Policies Scenario
SVS	Health Surveillance Secretariat
SWOT	Strengths, Weaknesses, Opportunities and Threats
TGC	Tradable Green Certificates
TIR	Internal Rate of Return
TR	Terms of Reference
TWh	Unit of measure of energy equivalent to 1000 GWh, that is, one billion of kWh
USD	United States Dollar
VPL	Net Present Value
WACC	Weighted Average Cost of Capital
WindSeeG	Offshore Wind Energy Act
ZEEs	Exclusive Economic Zones

SUMMARY

1 INTRODUCTION

1.1 Context and research problem

In 2019, global investment in offshore wind energy reached a new record, with the installation of 3.3 GW of new capacity in Europe alone. Offshore wind energy is attractive due to factors such as stronger winds and results, absence of restrictions on turbine size and lower environmental impact compared to onshore wind energy. In addition, there is potential for combined exploration with wave energy and opportunities for energy self-sufficiency for small islands dependent on fossil fuels (Redação, 2020).

In 2023, the second largest number of annual offshore wind farm installations was recorded, as well as the engagement of important policies for the sector, which prepares a solid foundation for the accelerated expansion of the industry in the next decade. The Global Council of Wind Energy (GWEC) forecasts that 410 GW of new wind capacity will be installed offshore, which aligns with the global goals of 380 GW by 2030 (ABEEólica, 2024).

Ben Blackwell, CEO of the Global Wind Energy Council, stated that policies in Asia-Pacific and the Americas are enabling the annual installation of record capacity, surpassing the 380 GW target of the Global Offshore Wind Alliance and aiming to triple that goal at COP 28 in Dubai. The sector is in the process of surpassing major markets such as European, Chinese or American, reached new markets in the year 2023 in rapid progress, from government commitments to economic growth to increased consumers and industrial decarbonization (ABEEólica, 2024).

The contracting of Brazilian wind projects in the 2009 Reserve Energy Auction has become the second largest source of energy in the country according to the Brazilian Association of Wind Energy (ABEEólica, 2021). In Brazil, the use of wind energy is concentrated in the onshore (terrestrial) type. Unlike what happens in other countries, such as the United Kingdom, which has several offshore parks and a very good expansion policy for this type of energy structured (Aquino; Peyerl; Santestevan, 2021).

Despite this, the best winds are located in the coastal region of the country, within the Exclusive Economic Zone (EEZ), as published by EPE (2020) in the Roadmap of offshore wind. Data from the geographic atlas of Brazilian oceanic coastal zones (IBGE, 2011) show that the country has an area secured by legal limits of the EEZ of 3,539,919 km 2, and currently 8,515,767 km², creating an area of economic development, scientific and social (Gielen et al., 2019).

The increase in spending on clean energy is supported by emission reduction targets, emissions, technological gains, energy security imperatives (particularly in the Union Europe) and an additional strategic element: major economies are implementing new industrial strategies to stimulate clean energy production and establish positions stronger market positions. In emerging markets and developing economies – a group that includes almost 85% of the world's population – energy demand has increased by around 2.6% per year over the last decade (IEA, 2024).

When it comes to the Declared Policies Scenario (STEPS), the deployment of energy clean accelerates as the pace of global energy demand growth slows, leading to a peak in all three fossil fuels before 2030. The growing reductions in coal demand mean that it is overtaken by natural gas in the global energy mix by 2030. Clean energy grows faster than total energy demand between 2023 and 2035. Led by the increase in solar photovoltaic (PV) and wind power, clean energy becomes the largest source of energy in the mid-2030s (IEA, 2024).

In the national market, Brazil has advanced significantly since 2012, when the energy auctions began to include contract guarantees for wind farms and from there the country reached the mark of 2GW of installed capacity, as a result of advances in manufacturing national wind turbines and components, with incentives from the National Bank of Economic and Social Development (BNDES) consolidating its leadership in Latin America (ABEEólica, 2012).

Since then, the evolution and its growing contribution to the renewable matrix is happening to this day, when the national supply of renewable energy in the electricity matrix in Brazil reached 89% in 2023; and the internal energy supply (IES), in the same year, registered a growth of 3.5% compared to the previous year. The largest share of consumption goes for transport and industry (BEN, 2024).

Estudos, no Brasil, acerca de expansão de energia renovável *offshore* considerando a inclusão da modelagem de geração de expansão de eletricidade a partir da perspectiva de menor custo, custo mínimo; pesquisas de utilidade econômica em que o foco está no aumento da escala de produção para reduzir custos, ou voltados a impactos no sistema elétrico são encontrados.

No entanto, há de ser considerada situações especificas de fazendas que envolvam variáveis com características ligadas a produção de energia *offshore* envolvendo relações de elasticidade e semi elasticidade de custo, o que ainda não foi encontrado em estudos de fazendas *offshore*, trazendo também o diferencial de ter como amostra do estudo os parques *offshore* localizados no nordeste do país.

Desta forma, eis o caráter inédito deste estudo, em que, através da pesquisa e levantamento das variáveis do sistema eólico onshore e *offshore* já implantados e a serem implantado no país, será descrito uma Modelagem de estimativa de custo inicial, CAPEX, com características de geração idênticas, e considerando as restrições existentes em cada região.

Assim, a partir da compreensão da complexidade dos sistemas onshore e *offshore* que necessita de complementaridade com outra geração não eólica; bem como do levantamento das variáveis necessárias ao estudo de um modelo baseado(a)s em econometria, tornar possível a associação entre geração, transmissão de energia renovável e acesso a eletricidade confiável, sustentável e moderna, consolidada pela meta sete dos Objetivos do Desenvolvimento Sustentável (ODS) da Organização das Nações Unidas (ONU).

Por conseguinte, diante do contexto relevante no qual está inserido esse tema, o caráter original e contributivo deste estudo estão nos seguintes aspectos: levantamento do atual cenário da energia eólica *onshore* e *offshore* local e nacional e evolução da energia renovável que se apresenta como de caráter relevante para o conhecimento interno e externo do país; representatividade dessa matriz energética na região para captação de mais investimentos; e proposta de um modelo de estimativa de custo (CAPEX) através de análise de variáveis quantitativas em parques *offshore* do Nordeste em fase inicial de investimento.

1.5 Estrutura e conteúdo da tese

Considerando o panorama exposto, a pesquisa está estruturada da seguinte forma:

O Capítulo 1, Introdução, descreve em que contexto se insere a expansão de geração de energia eólica *offshore* no país, a problemática da pesquisa, os objetivos os objetivos geral e specific ones to be achieved, the justification for carrying out this research, as well as the multidisciplinary and unprecedented nature of the study.

Chapter 2 presents the theoretical foundation, divided into: Overview of the characteristics of offshore energy; Description of components, structure and connections of a wind farm; wind energy legislation in Brazil; Offshore Energy and Winds in Brazil; Explanation of wind energy and Viability of the Offshore Wind System

Chapter 3 presents the scheme adopted for the construction of a scientific work, describing the methodological aspects applied to achieve the proposed objectives: characterization, typology, operational aspects, data collection and processing instruments.

Chapter 4 presents the presentation, analysis and interpretation of the results obtained considering the general and specific objectives defined as well as the methodological strategy applied to the study described in the previous chapter.

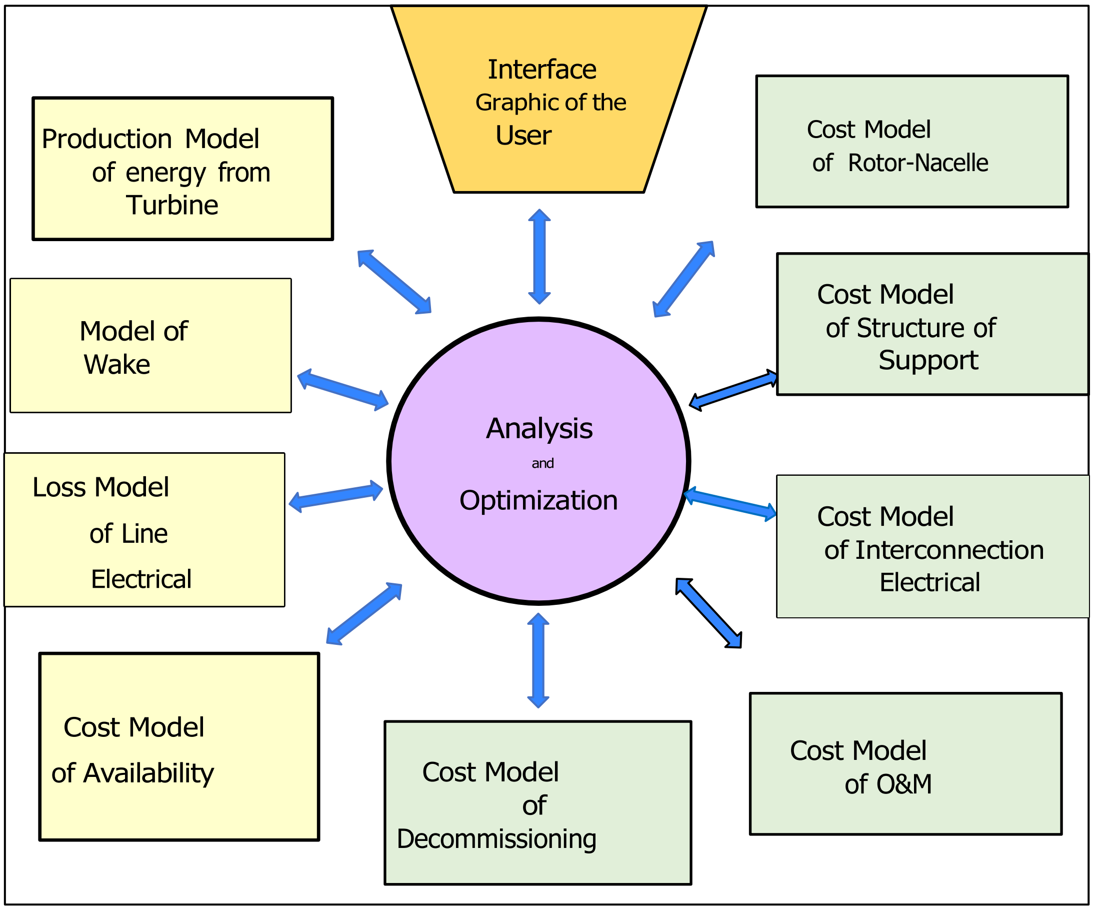
Chapter 5 reports the conclusions from the results achieved from the point of view economic, social, environmental or political; the contributions of the study, in addition to limitations and recommendations for future research and development of offshore parks.

Finally, the bibliographic references that were instruments of deepening on the study theme described in this work are described.

2 Introductory approach to offshore energy

The concept of offshore wind turbine was first proposed in 1930 by German engineer, Hermann Honnef. Writing about the topic occurred in the United States of America (USA) in the 1970s by Willian Heronemus. The installation of the first offshore wind turbine in the world took place in the city of Nogersund, Sweden, in 1990, and the installation of an actual wind farm occurred the following year, in 1991, in Denmark, as reported by Elkinton et al. (2008). The study by this author proposed a analysis model called Offshore Wind Farm Layout Optimization (OWFLO), formed by several mathematical models that estimate the contribution of energy components and cost of an offshore park, as shown in Figure 1 below.

Figure 1 – Components used in the OWFLO Analysis Model



Source: Adapted from Elkinton et al. (2008, p. 3).

A synthesis of the Production Models described by Elkinton et al. (2008) above mentioned can be described as follows: the subcomponent Energy Production Models (or

Energy Model) that uses wind data and the turbine power curve provided by the manufacturer to estimate energy production.

Alternatively, the rotor power can be calculated using a power curve generic based on the rotor diameter. Then there is the Wake Model represented by the PARK model, suggested by Katic et al. (1986), which is used to predict airflow and wake characteristics in a wind farm, which is a crucial factor in determining its total power. Then, they refer to Electrical Losses, for which two models are considered: one more complex, based on the theory of transmission lines, and another empirical, of losses in transmission lines.

The Availability Model described by Elkinton et al. (2008) defines the availability of the wind farm as the percentage of time it can produce electricity, being assumed at 95%, based on the DOWEC study, which indicates a small contribution of the layout to this metric.

As for the subcomponent, Cost Models, the following items are included:

- the Levelized Cost of Production (LCP) used to represent the cost of energy, considering capital cost, operation and maintenance costs, annuity factor, and annual energy production;
- the Rotor-Nacelle Assembly (RNA) Model, based on an empirical model, predicts the cost and weight of the RNA based on the rated power of the turbine;
- the Support Structure Model covers the support structure, which includes tower, substructure and foundation, being based on IEC standards and on factors such as wind loads, waves and soil bearing capacity. Different foundations are considered (gravity bases and monopiles);
- the Electrical Interconnection Models responsible for collecting and transmitting electrical energy from the park to the coast, using medium and high voltage cables, with cost modeling based on empirical relationships from existing parks;
- the Operation and Maintenance (O&M) Model can be based on a fixed percentage of the capital cost or on a fixed cost per unit of energy;
- the empirical Decommissioning Model, which is based on reports on the subject, addressing the dismantling of the wind farm.

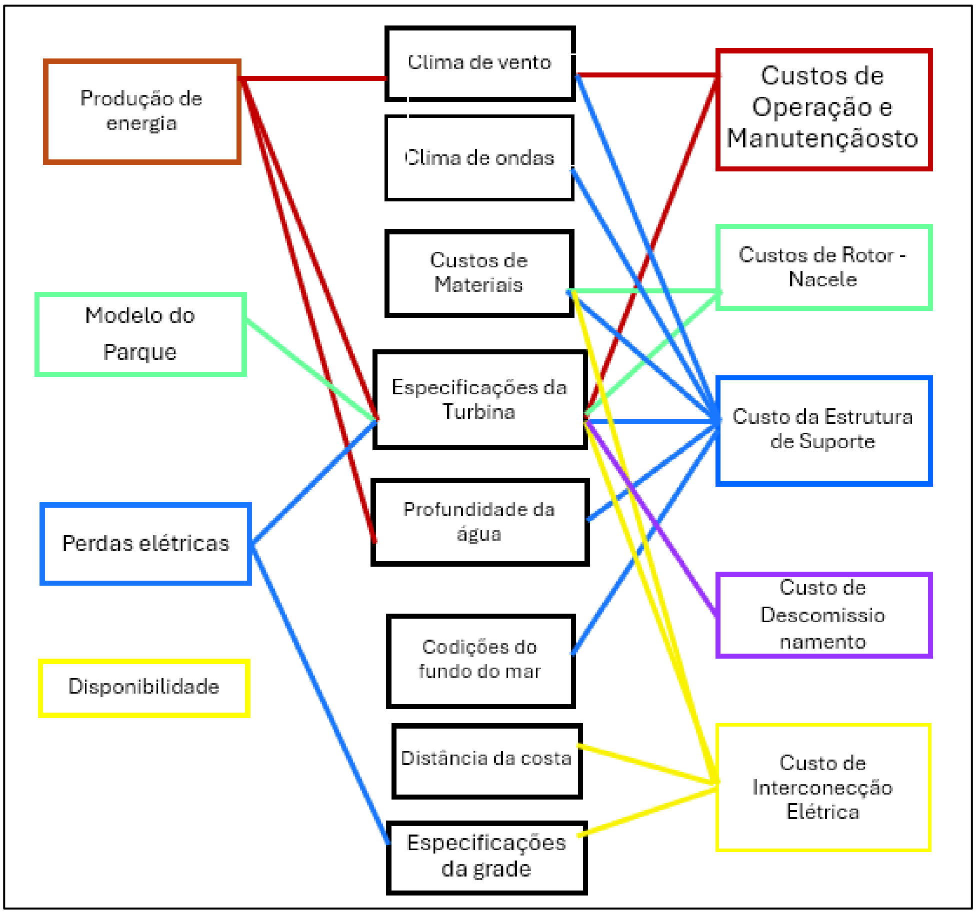
The main inputs for the individual analytical models, presented by Elkinton et al. (2008), are illustrated in Figure 2. The process described in this figure highlights the subcomponents of the energy model divided into two categories, namely:

1) Energy Model; and

2) Cost model.

This study was initially developed and improved over time, with the course of changes added to the process, which brought flexibility in the structures of offshore wind farms and significant technological improvements to the process, increasing efficiency and modernity.

Figure 2 – Main inputs of the energy and cost models



Source: Adapted from Elkinton et al. (2008, p. 3).

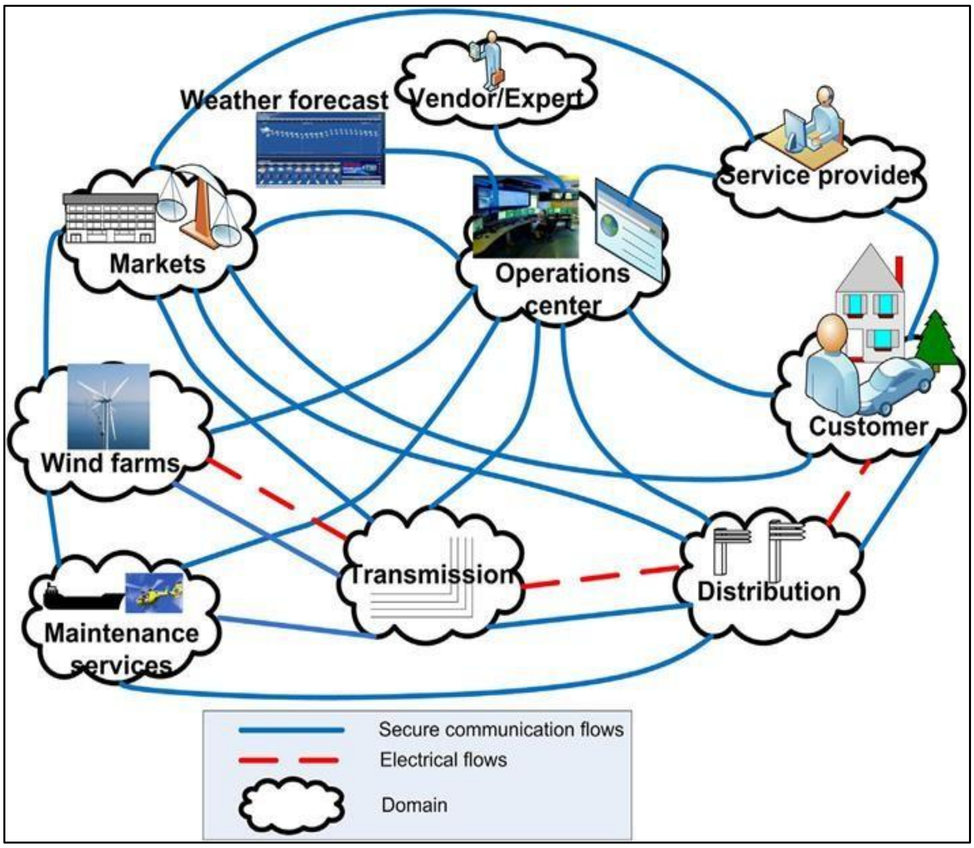
Given the characteristics of this energy model, the need for optimization of activities inherent to the challenges of implementing this energy matrix is noticeable, since the development of this type of energy has a high total cost, and, as Nguyen et al. (2013) report, improved operation and maintenance practices of these farms can result in a reduction of these costs.

Another study conducted by Nguyen et al. (2013) disregarded the installation stages, construction and decommissioning, and focused the study on the operational phase of a park offshore wind. This is because, according to these authors, the optimization of operation and maintenance are of fundamental importance in maximizing park yield, mainly because these two phases account for between 25 and 30% of the cost of energy generation.

From this perspective, the study they carried out reports that different specialized knowledge and various types of data should be combined in the optimization of this process.

The integration and communication of these processes is represented by a flow bidirectional, as shown in Figure 3, below, which denotes, among other issues, that there must be communication between wind turbines, between the operations center and personnel of maintenance, and communication with other wind farms with the objective of optimizing production.

Figure 3 – A conceptual model for offshore wind communications



Source: Nguyen et al. (2013, p. 2).

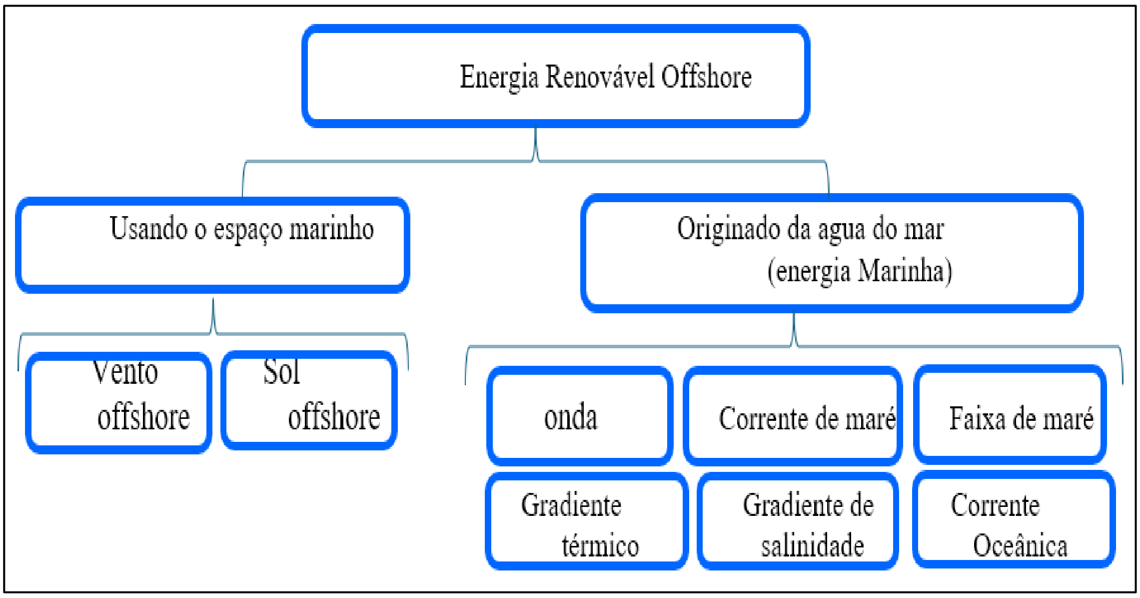
The communication network presented has an operations center that includes weather forecasting, markets, offshore farms, maintenance services, transmission and energy distribution, the customer and the service provider, the specialist and the supplier. The data from different sources and different expertise that provide information increase the efficiency of offshore production activities, reduce the cost of production and contribute to maximizing the result.

In addition, optimizing this network of connections integrates and supports activities offshore and allows sharing of experiences among those involved in this process. Therefore, consequently, the importance of an integrated structure lies in the greater availability of data, allowing for better decisions, reducing costs, and improving recovery rates.

The concept of "offshore renewable energy" includes a range of energy technologies less polluting, whose stage of maturity is different. The most important marine renewable energies are offshore wind energy and wave energy (Castro-Santos et al., 2024).

In this line of evolution of renewable energy resources, it is worth noting that recent studies by Shadman et al. (2023) report that Offshore Renewable Energy (ORE) sources can be divided into two categories, as shown in Figure 4, below.

Figure 4 – Offshore renewable energy categories



Source: Adapted from Shadman et al. (2023, p. 2).

The first is marine energy, which includes sources originating from seawater and is defined as energy captured by technologies that use movement, heat, or potential chemical. It includes ocean surface waves, tidal range, currents, gradients thermal and salinity, and ocean currents. The second includes sources available in space oceanic, such as offshore wind and floating solar energy (Shadman et al., 2023).

Taking this recent approach as a reference, wave energy and energy offshore wind stand out for the potential of offshore renewable resources available in continents bathed by the sea, enabling the diversification and flexibility of the matrix energy in these areas to meet energy demand efficiently and sustainably.

From this perspective, the exercise of stakeholders in advancing towards an energy matrix increasingly clean, has intrinsic value towards the joint commitment of a planet socially and environmentally responsible, and with purposes beyond growth focused so only for economic return.

From the perspective of renewable energy growth, there are factors identified as important for the growth and success of offshore farms, ranging from expectations of increasing energy demand, primarily on the coastline due to a larger core population to resource purposes, grid stability, and industrial production capacity. Others are identified as conditions for evaluating the possibilities of success: political support, implementation of new experimental infrastructures, access to data related to energy resources, electrical grid and industrial capacities, capacity for innovation etc. (Shadman et al., 2023).

Consequently, the variants involved in offshore energy production are interconnected in these models that reproduce reality and define representative metrics of the operations of this new technology. Beyond what is stated, it is worth describing the structure of this energy source.

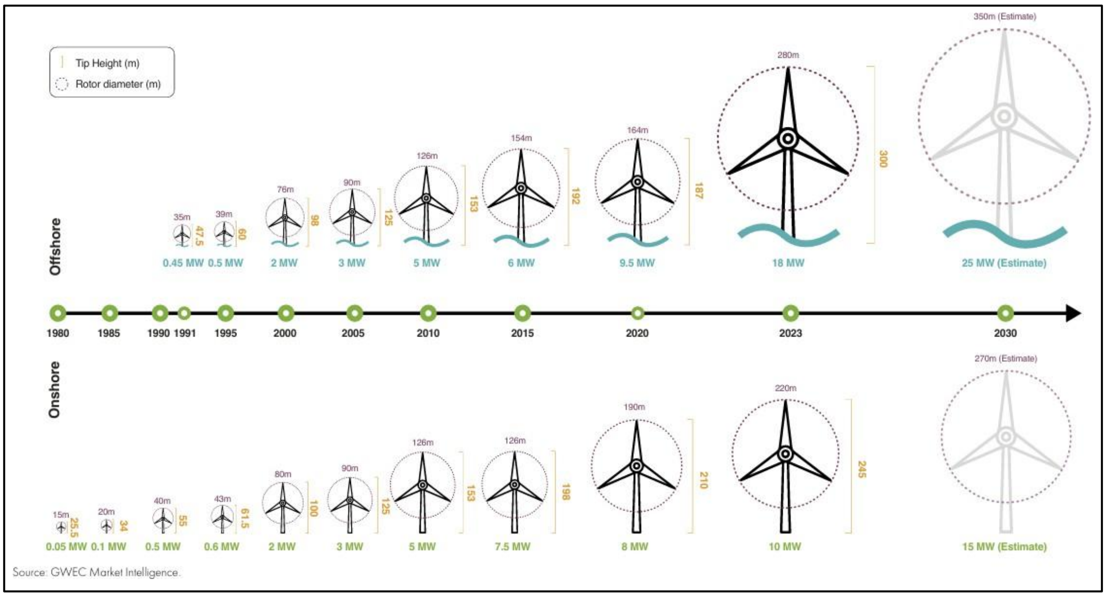
2.2 Offshore park: components, structure and connections

Obtaining energy from the winds requires the construction of a structure to maximize this resource in the electricity sector, and mega-structures are developed settled on the seabed and equipped with the latest technological innovations (ECICLE, 2020). Understanding how these structures work is the first step in addressing the estimates of the costs involved in these facilities.

The wind turbines developed over the years have shown evolutions in their structures, mainly in terms of the size of the turbines, with a tendency for more evolution, which can be observed in Figure 5. However, according to Johnson et al. (2001), the problem persists with the cost of capital, which is high in all models developed over the years.

As described by Gonçalves (2022), the competitiveness of the plants also depends on the allocation of these costs, which varies from country to country. In some cases, the assets transmission assets are owned by the national or regional transmission network owner and, in other cases, such costs must be incorporated by the offshore, further increasing the cost of energy.

Figure 5 – Trend of onshore and offshore turbine size, 1980-2030



Source: GWEC Market Intelligence.

The equipment that makes up an offshore park is expensive, and therefore the cost of an offshore park will only become smaller as the size of the park increases. In addition, the minimum size of a park should be at least 100 generators with a peak production of 20MW, as such components can promote changes significant in projects.

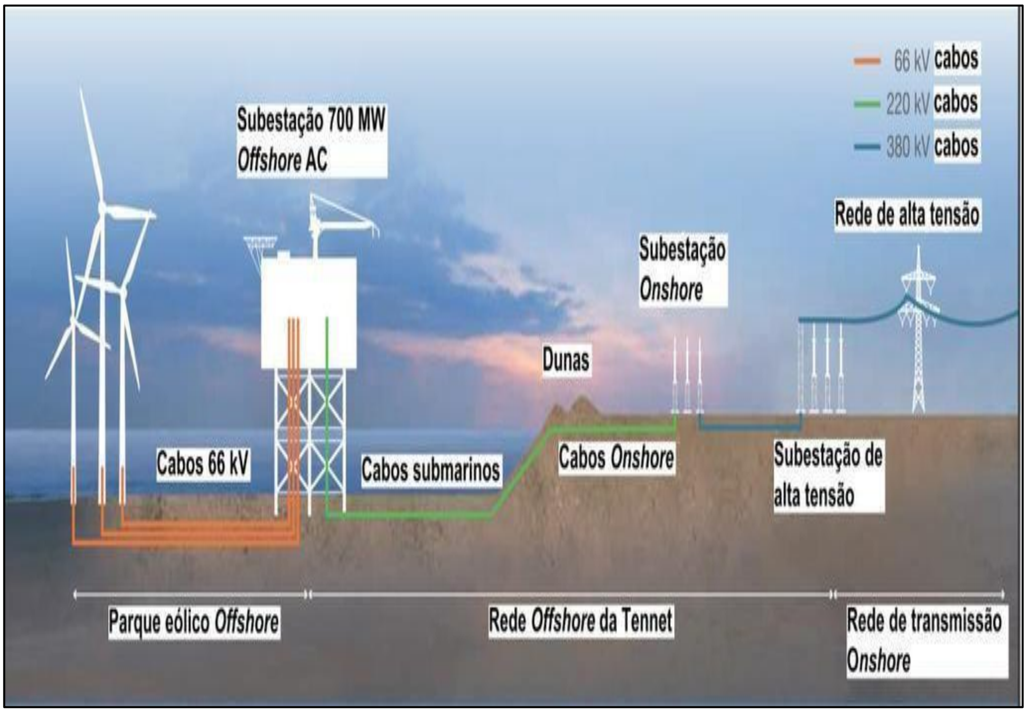
The use of offshore wind energy to replace a generation system electricity with base load by fossil fuels is presented as an important focus of study, given that most of the utility-scale energy storage existing in the world is pumped hydro storage.

The feasibility of offshore wind farms is also linked to the connection system adopted, which is closely linked to the total energy generation capacity and distance of these parks to the coast. This is because of energy storage.

a) Components and structure of a wind farm

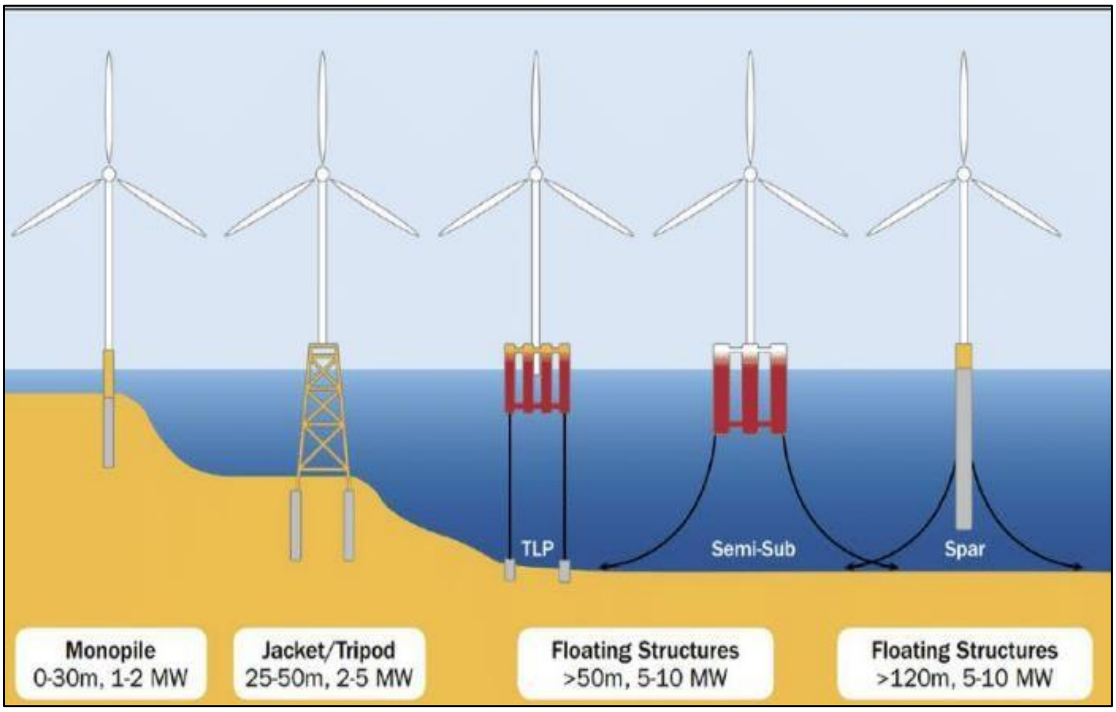
Understanding how this energy is generated can be clarified through the presentation of Figure 6, shown below, which is composed of the following elements: a) wind turbines; b) offshore substation; c) export cables; d) submarine cables collectors; e) onshore substation; f) high-voltage substation; g) high-voltage grids Figure 7 presents the types of structures available today and Figure 8 illustrates the loading, deployment, and installation of electrical equipment.

Figure 6 – Main components of an offshore wind farm



Source: Troll wind power.

Figure 7 – Structures with fixed and floating foundations



Source: Adapted from Manolas (2015, p. 3).

According to Figure 6, presented earlier, offshore wind farms are connected to the mainland through submarine cables which are insulated and the configuration of the network must take into account transmission planning studies, which require specific information on: available potential, location and characteristics of the systems for connecting each offshore wind farm approved by the bodies responsible for approving the deployment of the park. According to Figure 7, the depth and structure of the foundations of the wind turbines is also important.

Figure 8 – Loading, deployment and installation of equipment

Source: Global Energy Group Offshore Wind (2024).

In this context, the need for a robust port structure to support the construction, transport and assembly services of equipment to assist the offshore industry, as can be seen in the United Kingdom and Scotland, where the aforementioned services are occurring for products with fixed and floating structures.

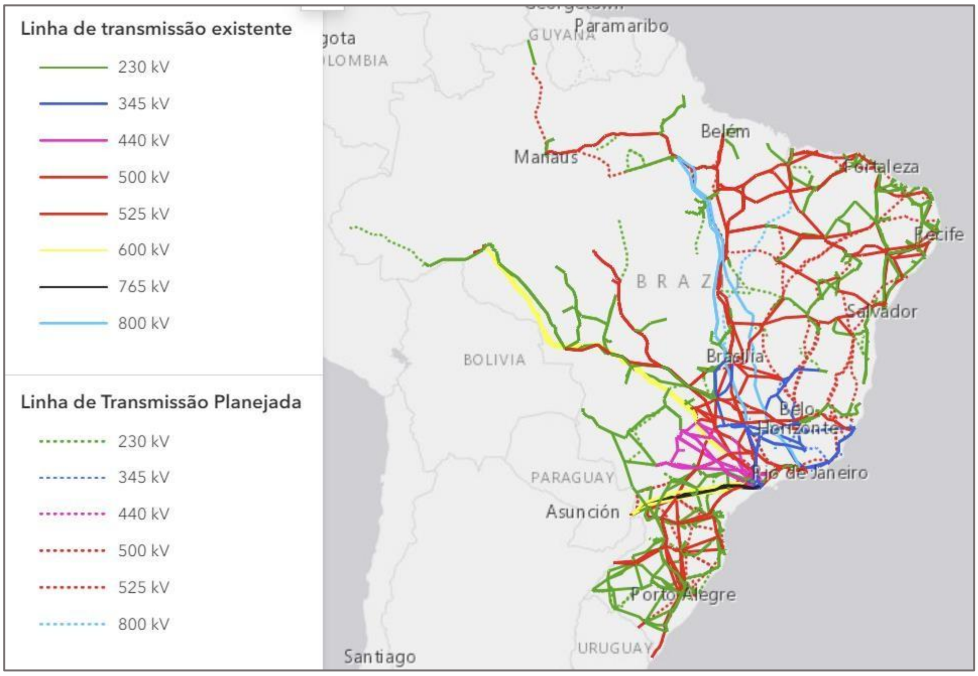
b) Storage and Connections of offshore wind farms

Wind power generation can drive cutting-edge cities to develop. This assignment causes what is called the Integration of Renewable Energies in the Sustainability of the Electricity Distribution Network. Among countless reasons, there is the improvement of the quality of energy, in which areas of difficult access can receive the benefits of a type of balanced and low pollution energy, from renewable sources, which help to promote its development.

Networks have become a bottleneck for energy transitions, but investment is increasing. After stagnating at around US$ 300 billion per year since 2015, it is expected that spending has reached US$ 400 billion in 2024, driven by new policies and funding in Europe, the United States, China and parts of Latin America. Economies advanced and China account for 80% of global network spending. Investment in the Latin America has almost doubled since 2021, mainly in Colombia, Chile and Brazil, where the spending doubled in 2023 alone. However, investment remains worryingly low elsewhere (IEA, 2024).

Brazil has a transmission grid or line, according to the EPE (2024), as can be seen in Figure 9. Electrical systems are interconnected through the grid of transmission of a large hydro-thermal-wind system, the National Interconnected System (SIN). The technology applied to the transmission network has the function of transferring energy between the subsystems, and can vary in two forms: direct current (DC) transmission and alternating current (AC) transmission.

Figure 9 – National Interconnected System (SIN)

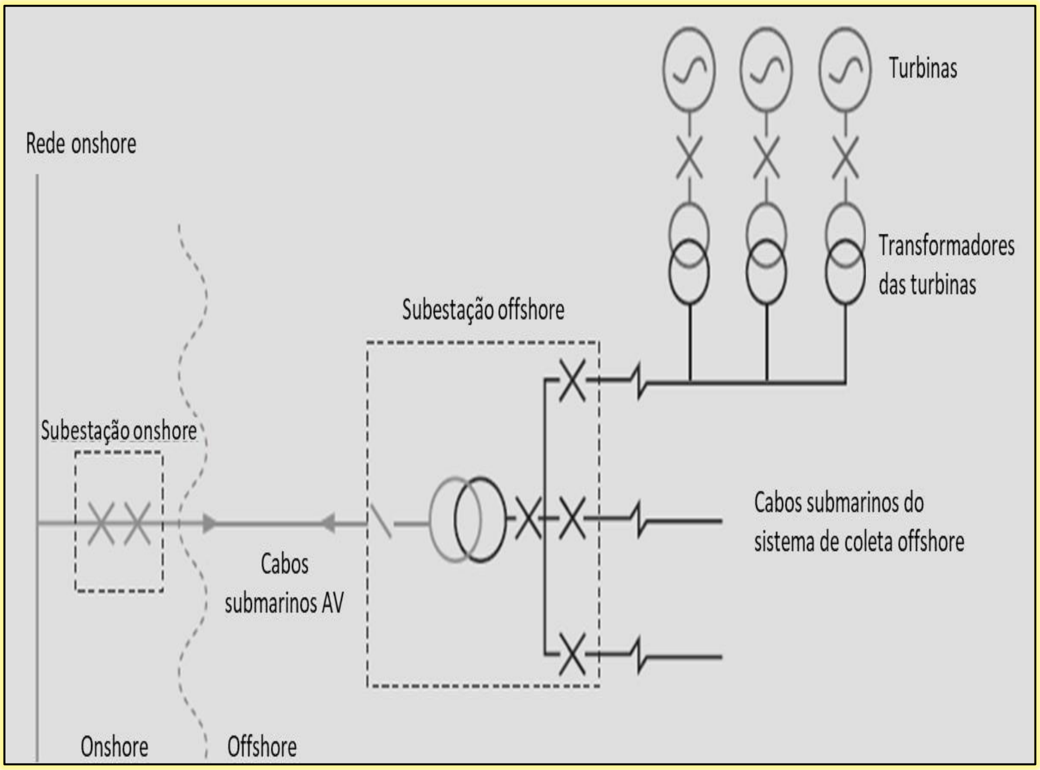


Source: EPE and MME (2024).

With regard to the necessary connections in this type of energy generation, several innovations have emerged in cables and substations for offshore wind farms, and described by reducing costs and increasing efficiency. Among others, LFAC technology, applied to cables, minimizes losses and costs in distant parks (between 60 km and 200 km). Dynamic cables have also been developed to support movement and barriers on platforms floating, being ideal for great depths. In substations, the advancement of versions floating stands out for offering an economical solution for installations in deeper waters. depths.

The electrical infrastructure of an offshore park is presented in Figure 10, below, being formed by wind turbines, inter-turbine submarine cables, offshore substation (when applicable), submarine transmission cables to the coast, onshore substation (and onshore transmission), and connection to the grid (Gardner et al., 2009).

Figure 10 – Diagram of the electrical infrastructure of Offshore Wind Farms



Source: Gardner et al. (2009 apud Silva, 2019).

According to Gardner et al. (2009), the offshore substation reduces transmission losses to the coast by increasing the voltage, but it is dispensable in projects smaller than 100 MW, with distance less than 15 km from the coast and transmission voltage compatible with the grid (33 kV, for example). The most modern projects, which are larger and further from the coast, require one or more offshore substations.

2.3 Offshore energy and regulatory improvement

The exploration of offshore wind potential involves fundamental issues for its development such as: environmental licensing and concession model, publication of the model of reference for the preparation of environmental impact studies, adoption of a spatial plan marine for orderly occupation of the coastal space, among others.

Therefore, the criteria and procedures inherent to these projects are legislative contributions that should receive special attention so that they are known the environmental interferences caused by these parks.

In this way, even presenting common elements that can be replicated for new markets, the regulatory framework for environmental licensing of renewable sources of energy is specific to each country and the adoption of efficient policies optimizes its use of this sector. In the specific case of offshore farms, it is necessary to define the activities that can be developed in the Exclusive Economic Zone (EEZ), in addition to other factors of unique impact of offshore parks, which are addressed by environmental policies and rules and natural resources. (Brazil, 2022)

Thus, the path taken to compose the history of the legal and regulatory framework, becomes crucial for the implementation of offshore farms, and for this reason, they are listed below.

2.3.1 Regulation of offshore wind energy in the world

The whole world has invested in renewable energy, mainly due to the publication made by the World Meteorological Organization in November 2019, which reported that the result of greenhouse gases, between 1990 and 2018, increased by 43%, with carbon dioxide (CO_2) accounting for 80% of this increase, and concluding that the growth of gases of greenhouse effect a long-term trend, with more damaging results to the climate in the future (AK-BHD, 2021). This fact reflects the importance of expanding the renewable energy matrix in countries committed to sustainable development.

The categories of actors involved in this matter include public institutions, formal, such as the State, private sector organizations and Non-Governmental Organizations (NGOs) to financial institutions, consumers and the general public.

According to Cavazzi and Dutton (2016), the first comprehensive analysis of wind resources in the Europe was the European Wind Atlas, published in 1989, however, this study only included onshore wind energy.

Regarding the offshore wind matrix, the promising development of this energy clean is linked to several studies combining regulation, technical feasibility, costs of installation; respective environmental impacts, wind speed, socio-cultural issues, advantages and disadvantages of this matrix, geographical factors, economic viability and characteristics of this energy, among other factors, as reported by studies by Silva (2019), Russell et al. (2021), Farias and Fontgalland (2022).

Neac and Word Bank (2010) considered as learning from experiences regulatory of the United Kingdom: the failures in the incentive system, called Renewables Obligatios (RO) that presented goals beyond the capacity to implement more technologies economic; the alignment between government energy policy and network regulation of the electrical sector; and also, the simplified concession process that contributed to rates of high success as well as for recovery of periodic capital costs recovered.

Spadoni (2023) reported that, globally, by the end of 2022, a total of 64.3 GW of offshore wind power capacity was in operation in 19 countries and three continents. More than 380 GW of sector capacity, in 32 markets, is expected to be added in the next ten years (2023-2032).

Virtanen et al. (2022), using a spatial prioritization approach, and rarely used in offshore wind energy planning, conducted an analysis of the potential for development of this energy in Finland, where the resolution of conflicts between biodiversity, social factors and economic profits proved necessary. The same authors reported that the deployment of offshore farms conflicts with several human interests, since the social acceptance of these projects involves sociocultural, political, economic and community dimensions.

Considering offshore sector technologies, innovation has occurred in many items that are part of this energy matrix. According to a survey of the status of innovations technologies in this sector, carried out by ABEEólica (2022), the following were identified developments:

- In the scope of planning stages, solutions for computational analyses stood out of forecasting and analysis of meteoceanographic and environmental data and programs for projection of future parks with reduced costs;
- Creation of more powerful turbines in order to expand the energy generation capacity at lower cost, in line with optimization of turbine manufacturing methodology, from the material used for manufacturing to its recycling capacity (the turbines offshore have the same specifications as the onshore turbine, but tend to grow to reduce costs per MW of installed power;
- Development of larger, heavier foundations for deep areas and foundations floating, lighter, to reduce cost, facilitate transport, deployment and operation of parks (this is because the type of foundation is installed according to the height of the water blade;
- Use of LFAC (Low Frequency Alternating Current) technology in the infrastructure electrical (cables and substations) for more distant parks, which allows reduction of losses and use of the dynamic cable that, due to its excellent mechanical resistance, fits its use in floating structure;

- Operation and maintenance activities managed by automation, digitization of procedures, artificial intelligence and other innovations linked to the technology of information;
- Innovations in port infrastructure and vessels through: management and coordination to optimize port logistics, creation of specific terminals and dedicated to the offshore wind industry, application of industry 4.0 solutions in the infrastructure port, decarbonization and creation of collaborative networks between ports and wind players, vessels dedicated to keeping up with the technological and size advancement of turbines, among others.

Regarding energy law, Del Guayo (2022) highlighted three principles structuring principles that emerge from the energy system itself and that he considered important because respond to the original needs of energy supply, namely; security of supply; economic efficiency; and environmental sustainability. Del Guayo (2022) defined such principles as authentic because they guide the energy system and because of their character permanent and not temporary, namely:

The principle of security of supply is of fundamental importance since guarantees that any consumer has access to energy consumption to satisfy this need at any time and therefore each country must apply this principle according with its characteristics; which is extremely important for the current energy transition.

The principle of economic efficiency requires that energy services be delivered at the lowest possible cost, through free competition in the market and freedom of business, without prejudice to the necessary regulation. This principle requires that the offshore energy generated assume competitive characteristics and a close relationship with cost-benefit.

The principle of environmental sustainability declares the requirement that products energy supplied produce minimal or no damage to the environment with a view to promote sustainable development. This portrays the interrelationship between regulation energy, environmental laws and climate change legislation. This principle highlights the importance of pursuing the prudent and rational use of natural resources.

Given the universal nature of these principles, any and all energy systems must implement them jointly and harmoniously.-. In this way, the application of these principles to offshore matrix chain both nationally and internationally, resulted in systems with reach in energy poverty and lower environmental impacts.

Virtanen et al. (2022), using a spatial prioritization approach, and rarely used in offshore wind energy planning, conducted an analysis of the potential for development of this energy matrix

The United Kingdom, an industry leader in Europe, has had 10 years of activity and generation of wind energy, surrounded by a productive chain of supplies and turbine installations, research, development and innovation and commercialization for the sector, possessing the largest wind complex offshore in the world. All this through the main Center for Research and Technological Innovation of the United Kingdom, for offshore energy, called Offshore Renewable Energy Catapult , created since 2013.

Barbosa (2018) reports that the strategy used for the development of offshore energy of this country was implemented through three rounds, in which the first defined guidelines for development and identification of areas for exploration and preparation of a Strategic Environmental Assessment (SEA); the second included the selection of fifteen projects on a scale commercial with a capacity of up to 33GW; and the third involved the criteria of the process of bidding, as well as proposals for the development of the zones in which the parks would be inserted.

With regard to Germany, the development of policies to increase the participation of renewable energy in its energy matrix resulted in the leverage of energy offshore on a scale, in 2002, despite the experience with the onshore sector having started in the years of 1990 (Wehrmann, 2020).

The German government adopts, for the consent of offshore wind farms, the First principle Come First Served (FCFS), in which permission is granted to the first interested party to submit a proposal, provided that the project does not pose threats to the marine environment, to navigation and national security, in addition to presenting a rigorous licensing system environmental, being submitted to analysis by government entities and environmental organizations, and broad public participation is allowed through public hearings (Barbosa, 2018).

Already in 2018, Germany began to auction offshore parks without subsidies, which passed to expose the auction winners to the competitive market risk due to the absence of extra remuneration per MWh generated (GWEC, 2018). According to Wehrmann (2020), in 2017, offshore plants were responsible for 3% of German energy production, and large part of them are owned by large companies, which did not happen with other sources renewables, which were in the hands of citizens, cooperatives and smaller operators.

Today, as Kyllmann (2023) reports, with a total capacity of just over 8 gigawatts (GW) installed at the end of 2022, Germany intends to reach 40 GW of capacity of offshore wind energy up to 2035 and 70 GW up to 2045, through a new plan for area development for the expansion of offshore wind energy, which defines: areas specific for wind energy in the North and Baltic Seas; the bidding years, commissioning and grid connections; establishes the basis for an electricity grid with permission of interconnection between European countries; and also defines an area for hydrogen production green offshore (with a total capacity of 1 GW).

Despite not being included in the 2022 list, Denmark was the world's precursor to install, in 1991, and decommission an offshore wind farm, in 2017, after producing 243 GWh of electricity, during more than 25 years of operation. After this feat, more precisely in 1995, the Danish government created the Danish Energy Agency (DEA), with the purpose of planning, approving and issuing licenses for offshore wind farms , as well as decommissioning and new grid connections.

González (2020) reported that Denmark's investment in offshore wind energy was driven, namely: by the NIMBY effect, which occurred after the implementation of energy wind power on land; by the visual and sound impact of wind farms on land; by the scarcity of land for onshore sites; and by the abundance of shallow waters with good wind resources.

The DEA makes projections of how consumption, energy production, electricity market, prices, among other variables will develop. This country has renowned manufacturers of turbines, such as Vestas, LM Wind Power and Siemens Gamesa (DEA, 2017; World, 2017). A peculiarity of Denmark is the participation of energy utilities and local cooperatives in offshore ventures, which started the participation of cooperatives and private investors in the development and corporate rights of parks offshore (Barbosa, 2018).

Thus, the Danish region presents excellence in offshore wind projects , as described by Energy (2022), given the maturity and experience in this sector, and by the differentiated character of popular participation which is quite active and acting; and of the how offshore complexes are built. Here, the investment depends on who chooses the location and area for park installation, as reported by Farias and Foutgalland (2022). That is, the first legal norm analyzed by this country is the concession of areas of exploration.

Regarding China, this country presented the highest level of growth in 2021, as 80% of the world's offshore wind power installed worldwide came from this country, which increased cumulative offshore installations to 27.7 GW, a level that took three decades to be reached by Europe (GWEC, 2022). In addition, the country has more than one hundred (100) nacelle assembly plants in operation and another 64 under construction, corresponding to 60% of the share in the global market, being the main turbine manufacturing center in the world (GWEC, 2023). This progress stemmed from its position as, in 2001, the second country that most emitted carbon dioxide, due to its dependence on fossil fuels.

Fernandes (2023) recorded that research related to technological development of this renewable source are concentrated mainly in foundations, aerodynamics of turbines and efficiency of generators, and that, currently, 55% of the supply chain of equipment for wind power generation comes from China.

The Offshore Energy Market Report (2022) recorded that, in 2021, China commissioned 13,790 MW — more capacity installed in 1 year than the entire world installed in any previous year. Barbosa (2018) demonstrated that the regulatory process in this country begins with the bidding for the granting and concession of an offshore park, whose responsible bodies range from the energy administration to the oceanic administration of the state, in addition to the participation of provincial governments, which also participate in the next stage, together with the central government, which corresponds to the elaboration of the zoning of areas suitable for offshore parks. The environmental impact assessment is conducted by the government, which directs the project to the specific authorities.

As reported by De Castro et al. (2019), the following are adopted as regulations documents: Renewable Energy Law of the People's Republic of China (2005, amended in 2009); Marine Environment Protection Law (2003); Law of the People's Republic of China on the Administration of the Use of Sea Areas (2001); Notice on the Measures Administrative for the Development and Construction of Offshore Wind Energy (2016) (National Energy Administration and State Oceanic Administration); Feed-in tariff for onshore and offshore wind (as amended in 2017) (National Commission of Development and Reform); Offshore wind development plan (2009) (Commission National Development and Reform); The 13th Five-Year Plan for the Development of Renewable Energies (2016-2020) (National Development and Reform Commission).

The study by De Castro et al. (2019) found that China, in fact, was in a position of transition from the coal economy to a sustainable energy model aiming at an even greater offshore energy development, through the substitution of policies of short term for more stable, comprehensive and detailed laws, by the introduction of a system of one-stop shop in the licensing process.

The USA started operations of its first offshore project in 2016, called Block Island Wind Farm. The Offshore Energy Market Report (2022) of that country recorded impacts caused by the Covid pandemic, by the conflict between Ukraine and Russia, which caused macroeconomic volatility, supply chain disruptions and inflation, which were reflected in offshore energy.

De Castro et al. (2019) also emphasized that there is a huge amount of legislation to be applied when it comes to the USA, distinguishing those that are applied in oceanic waters municipal, state, or federal waters, or even at more than one level, when, even being developed in federal waters, its cabling crosses state or municipal waters and that, among the laws that govern the development of offshore parks are: the Policy Law Energy (2005); the Federal Power Act; the Rivers and Ports Act; the Clean Water Act; the Law of National Environmental Policy (NEPA); the Marine Mammal Protection Act; Endangered Species Act; the United States Code; the Coastal Zone Management Act (CZMA); and the Outer Continental Shelf Act (OCSA). According to the authors, the overlap of jurisdictions and the lack of coordination between authorities and agents involved already caused difficulties in the processing of projects, and this is presented as an obstacle to the development of offshore plants.

When the subject is Europe, a pioneer in the development and implementation of specific technologies for offshore parks, Sweden stood out in second position on the list of the top ten world leaders in electricity consumption from renewable resources, in 2018, ranking only after Canada. A study carried out by Graczyk (2019) evaluated the development of offshore wind energy generation technologies in Poland and the results of this study showed that offshore energy technology can allow a cheaper energy production, compared to the dominant technology based on coal, already in 2030. Thus, the attractiveness of offshore wind generation, as well as onshore , resulting from the advances achieved, resulted in the concentration of component manufacturers of this activity in Spain, the USA, China, Denmark and Germany.

The Offshore Wind Development Program, developed by Colombia, was addressed by Schor (2023), as this country has high offshore energy potential, in thirteen regions. However, this study diagnosed the need to establish the regulation through the publication of laws or decrees.

A recent theme at the international level of the legal aspect of offshore wind farms was addressed by a research carried out by Nieuwenhout (2022) where the need to develop regulation for the Electricity Market of the European Union of the so-called hybrid asset (corresponds to a connection between two or more countries to which they are also connected, offshore wind farms). The aforementioned author reports the inadequacy of the current regulation for this purpose and suggests offshore bidding zones as a solution. This is because in the internal market model, they are only authorized to sell their electricity in only one country and the amendment of this legislation in the EU for the implementation of these rules is still outdated due to demand for a very long time.

In general, the procedures that countries have adopted for the development of offshore projects have presented different mechanisms, according to comparisons of research carried out by De Vasconcelos et al. (2022). This study highlighted the need for an assessment of the environmental impacts for the installation of the parks; of a standard and concentrated procedure, which was called a "one-stop shop" for granting all necessary licenses; and the creation of a Standard Procedures Guide for the environmental licensing of offshore farms. offshore.

The answers to this research show the need for a methodological procedure minimum so that the implementation process of offshore farms develops in such a way as to increase the participation of this energy in the global energy matrix.

And, as Castro Santos et al. (2024) pointed out, the European Commission highlighted that it is necessary to increase the installation of renewable energy systems and diversify them. This concern triggered the planning of the installation, by 2022, of an offshore wind capacity total of 30 GW, maintaining this region with the status of world leader in terms of installed energy, and boasting a capacity of 171MW in the offshore wind segment floating.

Thus, the efforts identified to expand and increase the diversification of the matrix global energy, and the validation of the government's commitment to expand this matrix energy, project the importance of developing and implementing the necessary legal framework to consolidate its implementation, since in Brazil, the Union exercises ownership over the Territorial Sea and the resources of the Exclusive Economic Zones (EEZ).

In this way, through the following explanation it will be possible to detail the steps and the current regulations that offshore parks need to be submitted to and how to proceed when of planning investment in offshore wind farms, and also, present the evolution of the regulatory process in the national territory.

2.3.2 Contribution of the National Environment Policy

The beginning of the formulation of environmental policies in Brazil occurred with Law No. 6,938, of August 31, 1981, named the National Environment Policy (PNMA), was responsible for including the environmental component in the management of public policies and created the National Environment System (SISNAMA). This law, updated in 2011, is a reference when it comes to environmental protection, in addition to directly stimulating the formation of an environmental awareness that leads to the exercise of shared responsibility established in the caput of art. 225 of the Environment of the constitutional text of 1988, which describes:

> Everyone has the right to an ecologically balanced environment, a common good of the people and essential to a healthy quality of life, imposing on the Public Power and the community the duty to defend and preserve it for present and future generations (Brasil, 1988).

This was the first step taken in favor of the environment, as its objective is the preservation, optimization and environmental recovery. When it comes to environmental laws, Brazil stands out for having one of the most complete legislations in the world. It also stands out in the PNMA, a set of 13 legal instruments, among which are included: the guarantee of sustainable development, the preservation of ecosystems and the promotion of the quality of life of the population. To achieve these purposes, especially in developing countries, it is necessary to guarantee the security of the supply of clean energy, referred to in the sustainable development goals, and universal access to energy services modern, quality, at comparable and non-discriminatory prices, these provisions, which are at the heart of the implementation of energy justice.

Intertwined with energy justice, Del Guayo (2022) reports, is Energy Law that defines this term as the part of law that assigns rights and duties regarding the exploitation of energy resources. Energy legislation, in the context of the development of markets international energy, has evolved, according to Del Guayo (2022), since the 1970s. In addition Moreover, according to the same author, the current content of this legislation is influenced by energy policies, whose economic regulation is an integral part of energy law, being considered one of its central issues.

In this same line of reasoning, studies carried out by Stroink et al. (2022) point out that energy law is the result of the influence of historical events that occurred in the country, which evolved from the awareness of the need to reduce the predominance of oil in order to reduce dependence on this source of energy, due, initially, much more to concerns about the unavailability of oil, than with environmental issues.

Some highlights of the evolution of energy law were pointed out by Stroink et al. (2022) and are presented below.

The first signs of decline occurred, initially, with the global oil crisis of 1973, which aroused the concern of governments and related bodies to raise alternative sources of energy. Therefore, until then, oil and gas were located in the heart of current energy law. The second global oil crisis occurred in 1979 and with it, the availability of this energy at affordable prices disappeared, triggering, then, the creation, under a special regime, of the National Electric Energy Agency (ANEEL), a autarchy linked to the Ministry of Mines and Energy, to regulate the electricity sector, through Law No. 9,427/1996 and Decree No. 2,335/1997.

Subsequently, during the 1980s and 1990s, the USA and Europe promoted political changes that were reflected throughout the world, with the liberalization of the market and privatization of public energy companies and this economic freedom resulted in the fact that increase the number of energy suppliers. Stroink et al. (2022) highlight that privatization and market liberalization proved insufficient, and the 1990s and 2000s was the period marked by the emergence of several regulatory entities and the approval of new standards that guided the competition of energy companies.

Stroink et al. (2022) highlighted, however, that free trade and privatization contributed to an intense internationalization of energy, new technologies and law energetic. The year 1997 was marked by the approval of the first international commitment to reduce greenhouse gas (GHG) emissions, for which the energy industry is the main responsible, known as the Kyoto Protocol.

The digital globalization of the 2000s increased energy efficiency, implemented technological innovation and incorporated new gas and electricity interconnections. The new technologies of communication and information provided cost reduction, better management of consumption and renewable energy generation. And these factors resulted in a more responsive quick to the demand for electricity and the interconnection of technologies and networks.

The course of the aforementioned events triggered, between the years 2010 and 2020, the concern with the need to guarantee environmental sustainability, reflected in the adoption of the 2030 Agenda, in 2015, which includes, in its objective number 7, the need to ensure that everyone has access to affordable, safe, sustainable and modern energy; in addition to concern with the adoption of an energy policy, through the Paris Agreement of 2015, where decarbonization was presented as a priority. In this period, more precisely in 2015, a new energy policy was adopted by the European Union, called "Energy Union".

Stroink et al. (2022) also pointed out a triad of principles essential to the purposes of the energy system, universal objectives, which the World Energy Council called the trilemma, but because they do not present potentially opposing content, they do not fit into this denomination, namely: energy security, energy equity and environmental sustainability. This triad is at the heart of energy legislation and guide current environmental justice.

When discussing regulation, specifically for offshore wind farms, De Vasconcelos et al. (2022) investigated environmental licensing procedures in the United Kingdom, Germany, Denmark and Taiwan and obtained as a result the structuring of eight guidelines: mapping of offshore maritime wind zones; development of studies environmental; adoption of a "one-stop shop" procedure; land concession regimes maritime: standard procedure guide for environmental licensing of wind farms offshore; among others.

This study, as reported by those responsible for the research, suggested and compiled the main strategies for optimizing environmental regulation of offshore parks and contributed to accelerating the development of this energy matrix in other countries, such as the case of Brazil, which is starting to implement these parks, as presented more in detail below.

2.3.3 Offshore Energy Regulation in Brazil

In addition to energy law, there is the regulation of the offshore wind sector, which in Brazil is still in progress. This is what is delaying the development of this activity. And, according to data made available by IBAMA, online, among other factors to consider, there is an overlap of offshore projects in the list of those that are in the phase of licensing at the agency, currently, which total 234,221 MW of power, distributed in 8 Brazilian states, as presented in Table 1. Table 1 shows the distribution of parks by state, with licensing in progress, including, in some, the overlap of the projects.

Table 1 – Distribution of offshore wind farms by state of the federation

State	1 RS	2 CE	3 RJ	4 RN	5 PI	6 ES	7 SC	8 MA	Total
No. of Parks	27	26	14	14	07	06	01	03	103

Source: adapted from IBAMA (2024).

According to the Brazilian Institute of the Environment and Renewable Natural Resources

(IBAMA, 2021a), the administrative process of licensing the installation, expansion, modification and operation of enterprises that intend to use natural resources, or that may, during the phases of the project, cause environmental damage, such as pollution and/or degradation, is described in the National Environment Policy (PNMA).

administrative process of licensing the installation, expansion, modification and operation of enterprises that intend to use natural resources, or that may, during the phases of the project, cause environmental damage, such as pollution and or degradation.

In the case of offshore wind farms, IBAMA, a federal agency linked to the Ministry of the Environment (MMA), is responsible for the environmental licensing of the park, established by the PNMA. Resolution No. 01 of the National Environment Council (CONAMA), of January 23, 1986, addresses the basic criteria and general guidelines for assessing the impact environmental impact of environment-modifying activities, such as ports and terminals for ore, oil and chemical products; Railways; electric power transmission lines, above 230KV.

The National Council for Energy Policy was established, together with the Policy National Energy Policy through Law No. 9.478/97, whose content encouraged research and development of renewable energy sources in Brazil. However, GCE Resolution No. 24/01, responsible for the institution of the Emergency Wind Energy Program (PRO-EÓLICA) was characterized as the first action aimed at wind energy. The impetus for the development of public policies for wind energy generation in the country was a consequence of the 2001 energy crisis, characterized by several blackouts in several regions of the country, which functioned as an emergency short-term measure, as there was no way to acquire, internally, the inputs necessary for the production of this type of energy.

It is worth mentioning that PRO-EÓLICA did not enable effective support for the development of this source, which only occurred with the creation of the Incentive Program for Sources Alternative Electric Energy (PROINFA), created in 2002, through Law No. 10.438/2002. This law established the increase in the participation of wind, small central hydroelectric and biomass in the production of electric energy in the country, effectively diversifying the matrix Brazilian energy, in addition to having: fixed prices, granted guarantees of energy purchase through 20-year contracts and financial resources with financing for the implementation of projects, by the National Bank for Economic and Social Development (BNDES).

With regard to offshore energy, the regulatory aspect for the development of this renewable energy in Brazil is still relatively recent, given that regulatory approaches starting in 2001 regarding the promotion of wind energy in Brazil, as mentioned above, PRO-EÓLICA, an initiative of the federal government, still only dealt with the onshore perspective.

At the beginning of the millennium, the Chamber of Deputies, through Bill No. 4673/2001, created the Priority Program for the Development of Wind Energy in the Northeast (PRODEENE), consolidating the development of this matrix in this region, and, more precisely in 2002, Brazil faced a new energy policy, whose incentives turned to biomass and biofuels from oilseeds. This process was called the new energy matrix. Wind energy was pointed out as one of the important vectors of this new wave, due to the fact that the Brazilian northeast coast produces favorable winds and cited in the IRENA report as part of the new energy production market (Farias; Fontgalland, 2022).

The first regulatory framework for wind energy in Brazil, Law No. 10.438/2002, described above, as Barbosa (2018) points out, fulfilled the role of introducing the first experiences in the wind area, however, with low regulatory requirements in the process of project selection, since the Environmental Installation License (LI) did not ensure priority for the qualification of parks with greater productivity and lower cost.

This is because the assessment of environmental impacts of energy generation investments electricity considered as low potential polluters, as is the case with offshore farms , may occur through studies with minimal content, in the preliminary licensing stage, called the Simplified Environmental Report (RAS); or even, through the Impact Study Environmental (EIA) together with its respective Environmental Impact Report (RIMA), called EIA/RIMA. In this case, the study is carried out in more detail through the stages of: Prior License (LP), where the location and conception of the project are authorized; Installation License (LI), in which the construction of the project is authorized; and, finally, Operation Licensing (LO), in which the operation of the project is authorized.

In addition, the same author highlights that Resolution No. 391/2009, created by ANEEL, national electricity regulatory agency, which regulates onshore energy, contradicted the current legal framework, since this body was attributed, only, the function of proposing adjustments and modifications to the legislation, and not the issuance of resolutions.

Law No. 10.848/2004 presented provisions for the commercialization of energy generated through Auctions of the New Energy and Alternative Sources type. The Energy Auctions of Reserves are regulated by Decree No. 6.353/2008. Thus, offshore energy could be bid in any of the types of auction, considering that the aforementioned law did not specified the type of investment in each one.

It is also worth mentioning that Law No. 10.438/2002 established the nationality of the equipment and services related to wind energy production and the chamber of deputies

altered this requirement, eliminating this prerogative, through Bill No. 1421/2007.
In that same year, two more Bills (PL) related to wind energy were introduced, namely: PL 2023/2007, which dealt with establishing tax incentives for the acquisition of goods and provision of services necessary for the use of solar, wind or other forms of alternative energy; and PL 220/2007, which established the deduction of expenses with acquisition of goods and services necessary for the use of solar or wind energy from the calculation basis of the income tax of individuals and legal entities and the social contribution on profit.

Subsequently, the Federal Senate, through PL 379/2008, provided for an incentive to the exploration and implementation of generation plants from wind sources, which ensured the right to 100% reduction in the tariffs for the use of electrical transmission and distribution systems, affecting the production and consumption of electricity traded in the environment of regulated contracting and in the environment of free contracting; and entrusted the National Agency of Electric Energy (ANEEL) with the setting or alteration of the discount percentage to the acts authorizing the generation projects covered by this law.

Other fundamental and necessary aspects for the development of this source, such as area concession models and aspects of offshore licensing, were not addressed in detailed form. However, still in 2009, specific auctions were established for energy wind power, with the denomination of energy reserve auctions (LERs).

In early 2010, prior to the offshore regulatory frameworks, the chamber of deputies instituted PL 7737/2010, which established the obligation to contract electricity from wind sources.

The year 2011 began with PL 1214, in which the Chamber of Deputies provided for the financial compensation to the States, the Federal District, the Municipalities and the bodies of the administration direct Union for the use of wind energy for the purpose of generating electricity.
PL 449/2011, instituted by the Federal Senate, whose content was to establish a reduction of the income tax of the individual incident on capital gain in the alienation of real estate equipped with equipment and systems for the use of solar or wind energy that provides at least eighty percent autonomy in relation to the public energy grid electricity, thus amending Law No. 11,196, of November 21, 2005.

In 2012, the Chamber of Deputies provided for two themes: the permission to deduct expenses with the acquisition of goods and services necessary for the use of solar energy or wind power from the calculation basis of the income tax of individuals and legal entities and the contribution social on profit, through PL 3097/2012; and on the exemption from the Tax on Products

Industrialized incident on the marketing in the domestic market of equipment, blades and towers for the purpose of generating wind energy, through PL 3422/2012.

Subsequently, in 2013, a proposal from the Chamber of Deputies, PL 5539/2013, which amended Law No. 11,488, of June 15, 2007, expanding the benefits of the Special Incentive Regime for Infrastructure Development (REIDI), for projects to generate electricity from solar or wind sources; and, from a proposal from the Federal Senate, PL 475, which dealt with the granting of economic subsidies in the credit operations for financing the acquisition of energy generation equipment wind and photovoltaic with reduced capacity.

The guarantee of incentives for the self-production of electricity from microgeneration and distributed minigeneration, which use sources based on hydraulic energy, solar, wind, biomass and qualified cogeneration, was a proposal from the Federal Senate, through PL 48/2014; and the obligation of the Federal, State and Municipal Public Power to use photovoltaic solar energy and/or wind energy in all buildings belonging to the public administration was a provision of PL 161/2015, authored by the Chamber of Deputies.

Subsequently, on June 18, 2015, the Legislative Chamber amended Laws No. 7,990, of 1989 and 8,001, of 1990, which provides for the payment of financial compensation to States, Municipalities, the Federal District and bodies of the direct administration of the Union for the use of wind potential for electricity generation, and other measures, through PL 1910/2015, published on June 23, 2015, but archived on January 31, 2019.

The next step was taken by the Federal Senate, which, through PL 705/2015, which legislated to exclude from the obligation of the legal reserve the areas in which they operate electricity generation ventures from wind or solar sources; amended the wording of §7 of art. 12 of Law No. 12,651, of May 25, 2012, which dealt with the protection of vegetation native; amended Law No. 6,938, of August 31, 1981; Law No. 9,393, of December 19, 1996; and Law No. 11,428, of December 22, 2006. In addition, it repealed Law No. 4,771, of 15 September 1965; Law No. 7,754, of April 14, 1989; and Provisional Measure No. 2,166-67, of August 24, 2001; and took other measures.

The exemption from Import Tax on equipment and components for generation unconventional renewable energy (solar, wind, biomass, small power plants hydroelectric and solid waste) was legislated by the Chamber of Deputies, through PL 5793/2016. PL 229/2016, which provided for prior consultation with indigenous communities for the purpose of granting concessions for electricity generation ventures from sources solar and wind and electricity transmission in indigenous lands, was legislated by the Senate

Federal, through which the indigenous people involved were guaranteed the right to express and debate about this type of enterprise.

Another instrument, PL 384/2016, aimed to amend the Agrarian Reform Law (Law 8.629/1993) to allow Incra to authorize the beneficiary of the agrarian reform to enter into contracts with third parties aiming at the exploitation of the potential for wind energy production or solar in rural properties, this bill being presented by the Federal Senate.

The regulatory mechanism for offshore energy occurred through Bill initiative No. 484/2017, which, according to Vaicberg et al. (2021), promoted the development of electricity generation in the territorial sea and in the exclusive economic zone, from the source wind power, regulating the rational use of marine energy resources from the concession of these zones intended for public service or self-producer, for powers greater than 5,000kW, being supervised by the Ministry of Mines and Energy.

In addition, this PL proposed an exclusive bidding process for offshore energy ; established monthly payment for the occupation or retention of area, based on a percentage applied to the amount of energy commercialized by the concessionaire, among others provisions.

In December 2018, through Bill No. 11,247/2018 (formerly PLS No. 484/2017), the federal senate regulated the expansion of institutional attributions related to the National Energy Policy with the objective of promoting the development of electricity generation from wind sources located in inland waters, in the sea territorial and in the exclusive economic zone; and the generation of electricity from solar sources photovoltaic, as described in Oficio nº 1.427(SF).

According to Agência Câmara de Notícias, the aforementioned PL authorized the implementation of plants at sea for the generation of electricity from wind and solar sources and defined that the platforms could be installed in the territorial sea (up to 22 kilometers from the coast) and in the zone exclusive economic zone (up to 370 kilometers). By this project, approved on November 29th 2023, by the Chamber of Deputies, it will be up to the Executive Branch to define which areas may be suitable for the installation of wind farms.

In addition, according to Poder 360 (2023), Bill No. 11,247/2018, included in its content: that regions, such as oil fields, maritime navigation routes to areas protected by environmental legislation will not be able to receive such projects; that in areas close to oil blocks, operators will have preference in obtaining the grant; and that a compensation will be paid to the government for the energy generated at sea. It is worth highlighting the criticism highlighted on this site, which this PL establishes, in its content, subsidy and the extension of term of contracts for thermoelectric plants for December 2050, violated the merit of the advance environmental and sustainability.

Continuing chronologically to the regulatory framework, in October 2019, the IBAMA (2019) launched a study on the impact assessment of wind farm complexes offshore, which aimed to develop training and knowledge exchange actions with the in order to subsidize the formulation of proposals for technical and legal standards aimed at environmental licensing of Offshore Wind Farm Complexes (CEOs) in Brazil.

The study by Vasconcelos et al. (2019), mentioned above, researched the specific laws of the countries members of the European Union, through the mapping of environmental decision-making models applied in Europe for this type of project, describing, in detail, stages, applicable legal standards, environmental impacts, forms of public consultation and concession of areas, among other factors, which greatly influenced the construction of the national regulatory framework.

This progression process triggered expectations and, in April 2020, the Plan of Energy Development for 2029 included wind energy as a candidate for expansion of the matrix energy, with estimates of an increase of approximately 17% of the installed capacity of the National Interconnected System (SIN).

Also in November 2019, the Energy Research Company (EPE) launched the Offshore Wind Roadmap Brazil, with the objective of identifying possible barriers and challenges to to be faced for the development of this potential in Brazil and point out some recommendations (EPE, 2020b). This was another disruptive research to boost the growth of this energy matrix in the country.

The accumulation of these studies resulted, in November 2020, in the creation of the Term of Reference (TR), by IBAMA, with the objective of defining guidelines and criteria that supported the preparation of the Environmental Impact Study (EIA) and the Rima for complexes maritime wind farms and subsidized the licensing process for this type of energy.

An evolution of the importance of the offshore matrix is also described in the Plan National Energy 2050 (EPE, 2020), which highlighted the following points: the improvement of wind generation forecasting; the importance of decommissioning forecasting in the environmental licensing; the recommendation of articulation between the actors involved (governmental and sectoral); and the improvement of the existing regulatory framework, among others.

Therefore, aiming at the legal certainty provided by a regulation, in 2020, studies carried out by EPE (2020b) identified challenges in the implementation of energy offshore in Brazil, which were then considered.

To contemplate the latest recommendations detected previously, and to continue to regulatory definitions pertaining to the topic, in February 2021, Bill No. 576/2021 was enacted, which was only approved on August 29, 2022. The heading governs the exploration and development of energy generation from offshore installation sources , thus considered those located in the area of the Territorial Sea, the Continental Shelf, the Exclusive Economic Zone (EEZ) or other bodies of water under the Union's domain.

Bill No. 576/2021 discriminated two types of government participation mandatory in offshore projects: the first, called a signature bonus, which corresponds to the payment made by the interested party to obtain the grant; the second, participation proportional, to be paid monthly, in an amount not less than 1.5% of the energy effectively generated and marketed. This PL also defined the form of distribution of the bonus and proportional participation; the forms of this energy source of right to use the Union's assets; the prior definition of the sectors that discriminate the areas of exploration; the procedures for submitting the areas made available for the exploration of these parks; the procedure for requesting a Prior Interference Declaration (DIP); and also the requirements mandatory for the qualification of interested parties.

Bill No. 3655/21, published in October 2021, was an instrument regulatory that modified the authorization by concession process, through bidding, for the formalization of the authorization grant for the exploration of offshore generating plants in the waters under the Union's domain, and instituted normative changes in Law No. 9,074, of 1995, and in the Law No. 9,636, of 1998. This Bill designated ANEEL as the responsible for this authorization, by means of a list of documents with a predetermined deadline, in addition to directing percentage of distribution of the amounts collected for the use of the public good and suggested the adoption of the chronological criterion for the definition of the availability of spaces in the area maritime.

In January 2022, Decree No. 10,946/2022 was published, which came into force only in June 2022. This document, which deals with the assignment of use of physical spaces and the use of natural resources in inland waters under the Union's domain for generation of offshore wind energy, defined that the contract for the assignment of use of area for activities offshore could be of two types: onerous, in which the exploration of a central electric power generator; or by free assignment of use, when it is for the purpose of activities of Research, Development and Innovation. This same decree reported that its complementation could be established through the edition of normative ordinances, a fact occurred later and to be described below.

The publication of this decree followed the non-traditional path of Brazilian legislation, which consists of the creation of the law, the decree and, finally, the ordinance, since, until that date, the approval of the Law was still in progress, but this procedure attributed greater speed, agility and greater legal and regulatory certainty to investments in this sector.

Baleroni (2022) reported that the aforementioned decree did not regulate the possibility of conciliation and overlapping of economic activity exploration on the same portion of water, however, it established that the implementation of hybrid projects would be contemplated by the joint standard of the regulatory agencies involved, the National Electric Energy Agency (ANEEL) and the National Agency of Petroleum, Natural Gas and Biofuels (ANP), this being the first step to overcome the obstacle of impossibility of obtaining grants due to the lack of definition of the criteria for the use of offshore areas, and further improvements and infra-legal regulation are still necessary. infralegal.

In October 2022, two important standards were published in the Official Gazette of the Union, complementary to Decree No. 10,946/2022. These documents were the result of a public consultation process that collected 378 contributions originating from 37 different bodies governmental, institutions, associations, universities, companies and agents of the electricity sector (MME, 2022).

The first, Ordinance No. 52/GM/MME, of October 19, 2022, established rules and complementary procedures for the onerous assignment of use of offshore power generation plants in the independent production or self-production of energy regime, described in article 5, item I of Decree No. 10,946, of January 25, 2022. This ordinance defined a deadline for the issuance of the so-called Prior Interference Declarations (DIP), and the systematization and unification of the rules and negotiation procedures in sales contracts for this matrix energy.

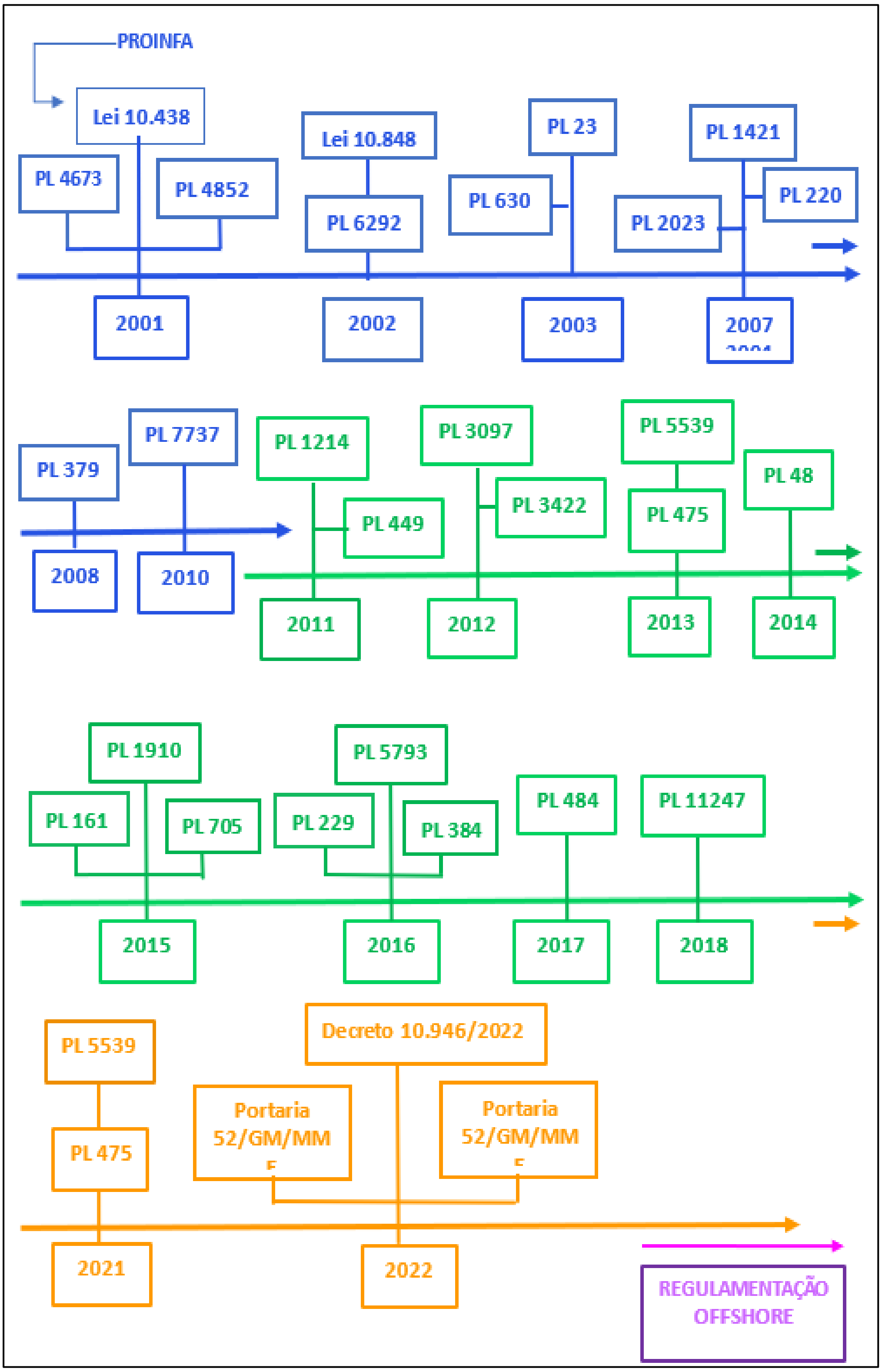
The second important standard was Interministerial Ordinance MME/MMA No. 3/2022, issued by the Ministry of Mines and Energy (MME) and the Environment (MMA), creating a online, public and digital tool: the Single Portal for Managing the Use of Offshore Areas for power generation, which came into effect on November 1 of the same year. A implementation of this Portal was based on the experience of countries such as Germany.

Are underway, in parallel to the publication of Decree No. 10,946/2022, and aim regulate the exploration of offshore parks in the country Bill No. 576/2021 and Bill No. 11,247/2018 (originally PLS No. 484/2017); in addition to Bill No. 3,655/2021, mentioned above. However, there are still important gaps in these ordinances and decrees complementary. One of them, describes ABEEólica (2022), is the definition of a methodology for calculating the value for the use of the public good, which according to this body, will define a value fair for the assignment of this source without burdening offshore projects and without penalizing the Union's gains too much.

Another gap concerns the maximum area granted to the same contractor in order to guarantee competition, and to follow international expertise that limits the extension of areas, of power, of energy density of the parks and, also, the number of areas assigned to each company in the same bidding process. This aspect represents, for Brazil, not only the guarantee of efficiency of the area granted, but also the diversity and competitiveness of the sector that grew 189.1 GW of installed energy capacity in Brazil, in 2022, where a percentage of 12.64 corresponded to wind energy projects, granted and in operation (ANEEL, 2023).

The path taken for the regulation of this source is growing as they are expanding research in innovation and technology. As already described, this evolution legislative in the country continues to advance over time and a schedule of the regulation of wind energy in Brazil is described in Figure 11, below.

Figure 11 – Timeline of wind energy regulation in Brazil



Source: Self-elaboration.

2.3.4 Legal challenges for the advancement of offshore energy

The potential of offshore wind energy in the country, in locations with a depth of 50 meters can reach 700 GW distributed throughout the Brazilian coast, according to the Brazilian Association of Wind Energy and New Technologies (ABEEÓLICA).

Considering what is presented in Table 1, there is a significant amount of energy offshore to be installed in the coming decades in Brazil. In addition to the installation and increase of cumulative offshore energy capacity, which will be expanded, there is an estimated increase in costs with cables for connecting this energy, due to the increase in distance between parks and the coast, and the interest in commercialization and increased reliability of the electrical system to interconnect offshore electrical systems to terrestrial grids when it comes to connecting two or more countries.

In the current scenario, the hybrid function of the offshore electrical infrastructure, which fulfills the dual function of connecting the offshore park with the terrestrial grid of two or more countries and serving as an interconnection between these countries, is a proposal that could be applied in Brazil, when an appropriate legal framework is developed. For this situation, it is worth highlighting a study carried out by Nieuwnhout (2022) where the author found that the connection of offshore energy and the increase in interconnection capacity can be combined through hybrid projects in the European Union, however, the current legal framework is not favorable due to the current regulation, still with a structure with flaws and gaps in the framework legal.

The study carried out by Wiegner et al. (2024) identified, through a review systematic, that licensing issues, gaps in legal frameworks, regulation rigorous in terms of safety and spatial competition are barriers to the offshore energy system and that the interdisciplinary aspect of offshore systems must be applied, instead of the technical-economic aspect, which only contemplates challenges of specific components of the infrastructure.

With regard to the aspects to be faced by the wind sector in Brazil, Silva (2023) listed challenges to be considered. Among them, the construction of a chain productive that generates a greater amount of indirect jobs; the modernization of equipment (wind turbines), making them more powerful and with national production; the improvement of the energy transmission line system, which is not sufficient for the outflow of the production of this energy generated in wind farms, among others.

In research carried out by Santestevan et al. (2021), the SWOT tool was applied and the points of interest of this technology were identified. As a result of this study were pointed out: the impact on the environment, the lack of national technology for power generation at sea, and the lack of specialized labor for this activity specifically (although the oil and natural gas industry presents part of the knowledge necessary).

It is important to highlight a compromising aspect of offshore energy regulation, which is that Decree No. 10,946/2022, which established rules on the assignment of use of Union areas bme as well as on the exploitation of natural resources in waters for energy production, may diverge from laws that may be enacted by bills (PLs) that are still being processed in the National Congress.

The reduction in the number of parties involved in the environmental licensing process, which in Brazil, begins at IBAMA, and passes through the National Indian Foundation (FUNAI), the Secretariat of Health Surveillance of the Ministry of Health (SVS/MS), the Palmares Cultural Foundation (FCP), National Historical and Artistic Heritage Institute (IPHAN), so that the environmental impacts of the investment, is another challenge that can be mitigated with the adoption of the one-stop shop, now discussed legislatively.

In this context, future perspectives are linked to the evolution of technology, the research and innovation in this market, which demands analysis and, sequentially, treatment adequate to implement the regulation of offshore wind farms.

In short, there is still much to be done to contemplate the entire legal approach necessary, in order to overcome important barriers, from licensing issues, gaps in legal frameworks, safety and environmental regulations and spatial competition. The legal dimension for achieving the integration of the offshore system through legal structures and robust governance encompasses the interdisciplinary scope and represents the master gear of future offshore platform scenarios.

2.4 Offshore energy and wind farms in Brazil

The theme of the environment is the second most common area for agreement between countries, second only to foreign trade (Barros, 2011). Within the scope of the matrix world energy, and considering the advances recorded by countries with more expertise, such as Denmark and the United Kingdom, the highlight, in 2022, for new farm installations offshore, was for the five markets: China, USA, Brazil, Germany and Sweden (GWEC, 2022).

The Global Offshore Wind Energy Report (2023) found that 2022 was the second best year for the global offshore wind industry, since, among other factors, were in operation, 64.3 GW of offshore capacity on three continents and 19 countries, representing 7.1% of global wind power installation. This stems from the awareness of intergovernmental energy agencies, companies and other climate-related entities that this is the way to achieve the goal of keeping warming at 1.5ºC until 2050, corroborating with the achievement of the Sustainable Development Goals (SDGs).

This theme comes from the Rio+20 Conference, in which 193 members of the United Nations (UN) met and initiated the guidelines for the creation of the SDGs, which resulted, in 2015, in the agreement of 17 SDGs, based on the social, environmental, economic and institutional dimensions to develop global goals and targets to be achieved by 2030.

Within this context, it is worth mentioning that the emission of greenhouse gases caused an increase in global temperature of 1.1 C in the period 2011–2020 compared to 1850–1900 and the emission of pollutants into the atmosphere has been relevant. and agreements were established with the aim of reducing global warming, mainly in the generation of energy through the participation of renewable sources, with the guarantee of a supply insurance. The generation and production of renewable energy is part of the context of the 7th SDG, "Clean and Accessible Energy."

Considering, also, the current world scenario, according to the International Association of Energy (2023), some of the tensions in the energy markets receded in 2023, after a period of prolonged and extreme turbulence since 2020, numerous risks remain and the current relative calm may not last, given that the continuation of fighting in Ukraine, more than a year after the Russian invasion, is now accompanied by the risk of a prolonged conflict in the Middle East, and, in addition, periods of extreme weather conditions are becoming a major danger to energy security.

Based on this chaotic scenario, the challenge for the implementation of the NZE (Net Zero Emission) plan, within the limits of the Kyoto Protocol, is to supply energy with characteristics of less impact on the environment, in which, of the renewable sources available currently, the one that has stood out the most is wind energy, mainly offshore, whether due to the great availability of wind, whether due to technological advancement, or even due to its promising commercial market.

Wind energy began to be used to generate electricity in the 1930s and with the increased concern with sustainable development, from the second half of the 20th century, as well as the recurring oil crises, this system went through improvements, which underwent profound technical and technological transformations.

The production of electrical energy occurs through the conversion of kinetic energy from winds into electrical energy, through a wind turbine, composed of: a rotor, on which the blades are fixed of the turbine that rotate with the kinetic force of the wind and transform this kinetic energy into mechanical energy; and a generator, housed in a compartment called a nacelle, which converts this mechanical energy of the rotor into electrical energy.

Only in 1992 was the first wind turbine installed in Brazil, in the archipelago of Fernando de Noronha, and the incentive to diversify this energy matrix began after the supply crisis of 2001, and currently, the country has been classified as a wind power, occupying sixth place in the Installed Capacity Ranking of the GWEC – Global Council of Wind Energy (ABEEólica, 2024).

According to Energy (2022), the scenario with striking characteristics and features of evolution, research, innovation and new ventures considering the best use of natural resources, reflects the importance of expanding and detailing studies about offshore farms. It is worth mentioning that offshore park installations are found, generally, in countries with little territorial range or strong maritime wind indices since in these locations, the wind speed can be up to 20% higher and the energy generated can be up to 70% greater when compared to onshore parks.

In the last twenty years, the growth of offshore energy has become visible to the eyes, through the incentive to invest in renewable energy source projects with emphasis on long-term strategies such as feed-in tariffs (FIT), which are based on fixed price or long-term premium; quota systems, including Renewable Portfolio Standards (RPS), combined with tradable green certificates (TGC); long-term auctions term; in addition to tax incentives and funded subsidies, as described by Ozato et al. (2023). These measures have provided faster adherence to this energy matrix and acceleration of the development of new technologies.

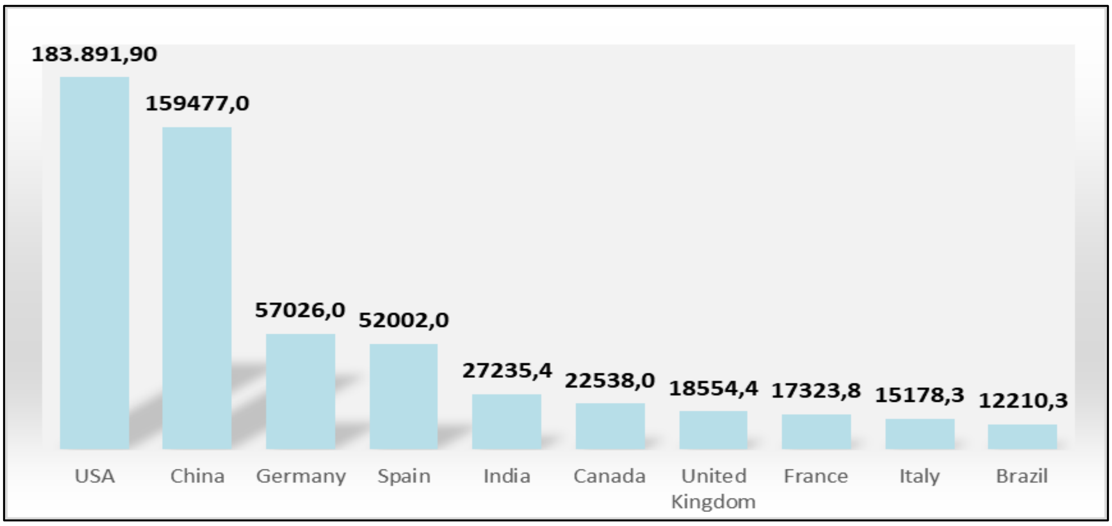
Corroborating Ozato et al. (2023), Castro-Santos et al. (2024) reported the need for increase in renewable energy system installations, and its diversification, highlighted by the European Commission, as this type of energy includes less polluting energy technologies. It also recorded Europe's position in the field of ocean energy (tidal energy and wave energy), with an installed capacity of tidal current energy of approximately 30 MW, far exceeding the rest of the world, which had a capacity of about 10 megawatts; and in the field of wave energy, the European contribution, in 2023, reached an installed capacity of approximately 13 MW, a value comparable to capacity of the rest of the world. According to Castro-Santos et al. (2024), wave energy has the advantage of being more predictable than offshore wind and solar energy, being, therefore, another path for research and development of clean energy production.

Another important aspect concerns the panoramic and regulatory context in which it is this theme is inserted, where, as cited by De Farias and Fontgalland (2023), presents the need for improvement since a structured and unified framework of the offshore wind source can result in legal certainty, greater transparency in instructions, predictability, in addition to reducing dependence on the country's hydroelectric and thermoelectric plants.

Worldwide, the evolution in the offshore wind sector has taken place in the countries of the North of Europe and Asian countries. According to ABEEólica (2023), more than 64 GW of wind offshore were installed and distributed, in a greater proportion between Germany (8.05GW), United Kingdom (13.92GW), and China (31.44 GW), while the remaining gigawatts were distributed in a smaller percentage to the Netherlands (2.83%), Denmark (2.31%), Belgium (2.26%), Taiwan (1.41%), among others. According to the Brazilian potential for offshore wind with depth of up to 50m, reaches the level of 700GW.

The national onshore wind sector only started generating electricity from 2014, as can be seen in Figure 12, when it ranked tenth place in the world ranking (which presents USA, China, Germany, Spain, India, Canada, United Kingdom, France and Italy, ahead of it), according to data from the International Renewable Energy Agency (IRENA, 2024).

Figure 12 – Onshore energy generation – ten largest countries in 2014 (GWh)



Source: Adapted from IRENA (2024).

With regard to the development of the offshore energy matrix, this modality is being developed in order to diversify national production sources, based on the agreement of cooperation between European countries that have excellence in this area, among which are Denmark, Belgium, Holland, United Kingdom. Other countries are currently standing out in the implementation of offshore complexes such as China and the USA, from investments in research and innovation, which have been carried out so far and which are important to integrate this source into the utility system and generate and transmit this energy.

The works on the development of this energy, published so far, describe important characteristics, namely: location (depth and distance from the coast); climate marine; wind farm layout; wind speed; decommissioning and destination of removed components; limited range of fixed platforms, etc. And, for this reason, the proper management should include integration, interconnection and planning of transmission. This detail was described through a study carried out by Smith et al. (2007), through which the interconnections of wind farms, their impacts operational, the planning of the transmission of this energy, as well as accommodation issues of the quantities of this energy in the system and market operation.

The aforementioned work obtained results through operational experiences in Europe with 40,000 MW of wind capacity, which served as a knowledge base in interconnection of wind farms for the United States, highlighting, including, the capacity of sophisticated machine models with electronic power control; the improvement of system performance through damping of power oscillations; and also support in post-fault voltage recovery, among other factors.

Aspects related to technical performance were also the subject of study by Denholm (2001), whose work evaluated the complementarity of this energy source (offshore) with biomass-based energy storage, which enabled a quick response to generation variations of offshore turbines.

It is worth mentioning that more comprehensive and detailed studies are relevant for both the country and the world. A notable example of the importance of studying expansion energy is in Brazil's National Energy Plan (PNE) 2050, which estimated, until 2050, a trajectory of evolution of potential energy consumption in a scenario of expansion challenge, with an average growth rate of 2.2% per year, and GDP per capita growth of 2.8% per year. on average in the period. In this context, the development of this energy matrix is characterized, not only for favorable technical aspects, but also due to the aspect of equality of energy distribution.

Studies, in Brazil, about the expansion of offshore renewable energy considering the inclusion of modeling the preference of interested parties in the decision analysis of energy planning have not yet been carried out, until then, by any research academic. Similarly, there were no studies that applied the methodology created and applied in photovoltaic systems, as described by Nock et al. (2020). What is in abundance in the literature are studies of electricity expansion generation from the perspective of lower cost, minimum cost; economic utility research in which the focus is on increasing the scale of production to reduce costs, or even studies focused on impacts on the electrical system, as cited in the same work.

However, when it comes to economic feasibility studies, the costs involved in offshore wind farms in Brazil are unknown because there is no practical information of offshore farms in operation in any region of the country, since these investments, even with expectations of rapid development, are still markets unexplored throughout the country, which makes it impossible to obtain real financial data.

What currently exists, according to IBAMA, are projects in development, distributed in eight states in the NE, South and SE regions of the country, still in the implementation phase, and, therefore, far from presenting real cost results. These projects are distributed among 22 entrepreneurs (Table 2), as described by the EPBR news agency website.

Table 2 – Investors in Offshore Wind Farm Projects in Brazil

Investor	(MW)	Investor	(MW)
Shizen	17.475	Cemig	4.500
Shell	17.080	H2 Green Power	3.000
Ventos do Atlântico	15.228	Beta Wind Energias	3.000
Bluefloat Energy	14.960	Internacional Energias	2.484
Equinor	14.370	Prumo Logística	2.160
Eólica Brasil	10.800	Chiri	1960
Geradora Eólica Brigadeiro	9.840	Votu Winds	1440
Neoenergia	9.000	Qair	1.216
TotalEnergies	9.000	Camocim	1.200
PensionDanmark(Bosford Partici)	7.305	Energia Itapipoca	720
Acciona	6.080	Com. Energia Humberto de campos	720
Alpha Wind Morro Branco	6.000	Pedra Grande	624
Kaanda RM Cunha	5.388	Bi Energia Ltda	576
Monex	4.920	Senai-RN	22

Source: Adapted from the website: https://brazilenergyinsight.com/2022/08/05/shizen-leads-offshore-wind-projects-in-brazil/?utm_source=chatgpt.com

The total number of offshore farm projects currently in the country is 103 units. Of these, 50 are located in the Northeast region, 22 located in the region

Southeast and 31 in the South region. The total area of these projects is 71,006 km and the total power corresponds to 244,564 MW throughout the national territory (IBAMA, 2024).

In this context, the offshore wind farms with projects in licensing at IBAMA are distributed in the states of RS, SC, RJ, ES, RN, CE, PI, and MA. The NE Region includes 26 farms with a power of 66,367 MW, located in the state of CE, plus 6,168 MW in MA, added to 25,468 MW in RN, plus 15,030 MW in PI, totaling 113,033 MW of power, corresponding to 46.22% of the total. The South Region, in second place, formed by the parks of Rio Grande do Sul and Santa Catarina, contributes, respectively, with 30 farms in the state of RS, with 75,908 MW of power, and with 5,700 MW of power in another farm in SC, representing 33.37% of the total. The SE Region, in third place, presents, registered in IBAMA, 6 projects located in ES, and 16 located in the state of RJ, which correspond to 49.924 MW, that is, 20.41% of the total.

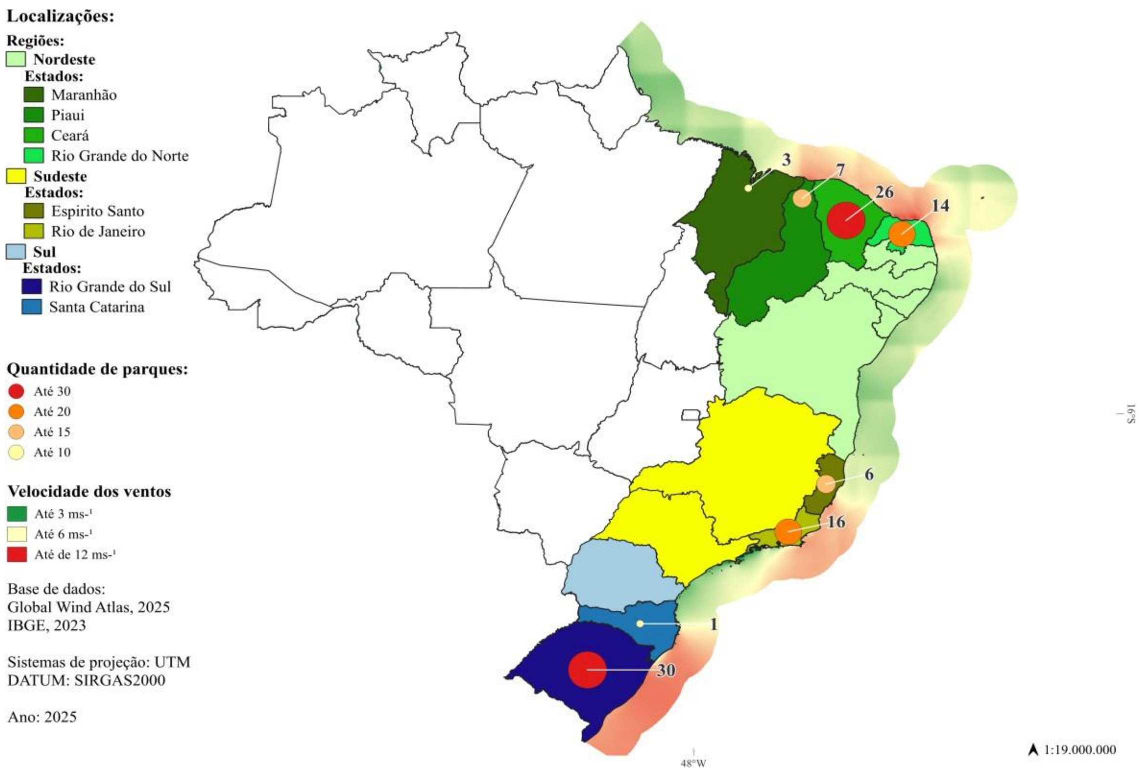
Considering the spatial distribution of these farms, at a national level, and the behavior of the winds as highlighted in Figure 12, and given the high number of projects in the licensing phase at IBAMA, the occurrence of overlapping is inevitable some, whose most critical situation occurs in the state of CE, with seven of its 26 projects overlapping, followed by RN, with five of the fourteen parks; and RJ with five projects of the total of sixteen, also with overlapping characteristics. Figure 13 also highlights the distribution of these parks in the Northeast, Southeast and South.

In this context, the problem of spaces destined for its implementation, as well as the overlap observed in is part of the context of licensing offshore wind farms, each project submitted to Ibama's analysis.

The delimitation of spaces and the solution for overlapping of these farms in the phase of licensing were evidenced when these aspects were included in the provisions on the regulation in the offshore context, through a decree, sanctioned in January 2022, the which provided for the assignment of use of spaces in the territorial sea, in the exclusive economic zone and on the continental shelf for offshore farms.

This decree is presented in more detail in a specific chapter of this work, which describes decrees, laws and other documents, during the approach about the regulation of offshore wind energy, in which the regulatory improvement is described of offshore energy in Brazil.

Figure 13 – Offshore energy farms in the licensing phase in Brazil



Source: IBGE, EPBR.

Note: QGIS software was used.

Figure 13 presents the information, identified by the intensity of color, of number of parks in each state and speeds between 3 ms-1 to 12 ms-1, since it is the speed, constancy and direction of the wind, essential factors for the installation of parks wind farms. This map also includes the best location of offshore farms in the territory national, and thus, the part of the earth's surface occupied by seas and oceans, which corresponds to more than 70% of the total and which also becomes productive for the development of this type of energy matrix (GWA, 2024; IBGE, 2023; EPBR, 2023).

2.5 Explanation of wind energy

Wind is the main component for energy generation and the calculation of production of energy in a wind turbine shows the cubic relationship between wind power and speed of the wind. Thus, as demonstrated by Johnson et al. (2001), the driving force of the movement of the air, energy generator, occurs due to the difference in air pressure between two regions, described by Boyle's Law (at constant temperature, the product between pressure and volume of a gas must also be constant); and by Charles' Law (at constant pressure, the volume of a gas varies directly with temperature). Thus, the wind speed increases with the increase in the pressure gradient and, under these conditions, a wind and pressure system is formed whose combination of high and low pressure areas with the Corilis force (deflecting force that alters the direction of air movement) result in strong winds with constant speed (on average of 8 to 14 m/s) and ideal for application in wind energy.

In this sense, to assess the wind energy potential in a location, it is essential understand the characteristics of the wind, such as speed, duration, continuity and direction. The profile of the wind can be estimated from long-term speed data, allowing an initial analysis. The distribution of wind speed is especially important for this assessment (Khahro et al., 2014).

Still in this context, the wind speed and the characteristics of the wind turbines to to be installed represent the maximization of energy production per dollar invested and, therefore, consequently, a wind farm should not, according to Silva et al. (2021), be installed in a place without a correct assessment of the availability of the wind resource in the region, as well as estimating the energy potential through wind speed.

Therefore, the construction of a wind and energy generation forecasting system wind power requires estimates of the spatial distribution of wind speed, the description of which has a direct link to the estimation of energy power. This is because the wind does not circulate at constant speed and this characteristic directly influences the amount of energy that can be generated by a wind turbine.

According to Equation I presented below, the wind potential increases proportionally to the cube of the speed, thus characterizing the non-linear relationship between the wind speed and power generated. That is, small variations in wind speed cause large changes in the power generated. Knowing the distribution of the most used statistical models allows calculating the energy generated considering these fluctuations. Among the most well-known and used wind models in wind studies, are: Kappa Distribution, Weibull Distribution and Rayleigh Distribution.

The wind speed suitable for wind energy purposes is one of the key factors for the choice of location of wind projects, and for this reason such studies are necessary. The energy available to a wind turbine is the kinetic energy associated with a column of air moving at a speed v (m/s), passing through the area A (m) of the turbine rotor, and moving a specific mass of air, ρ (kg/m³), at a speed v (kg/s).

The available wind energy P(W) can then be calculated by Equation I, as follows described. This equation denotes that the power obtained from a mass of air is proportional to three factors: the area of wind capture by the turbine, that is, the circle of area S (πr) swept by the propeller of radius r; to the local air density (ρ); and to the cube of the wind speed (v) (De Farias; Fontgalland, 2022).

Equation I – Available Wind Energy

$$\square(\square) = \frac{1}{2}\square\square\square\square\square^{3}$$

Where:

ρ = air density (Kg/m^3)

V = wind speed (m/s^2)

$S = \pi r^2$

2.5.1 Wind speed estimation

Wind speed is a random variable and its prediction is given through the probability distribution, with several models proposed in the literature. This topic was treated through several models of Probability Density Function. A Function of Probability Density (PDF) is a mathematical function that describes the probability of each member of a discrete set or a continuous range of outcomes or values possible of a variable. Several studies focus on selecting the best function of wind speed distribution (Mazzeo et al. , 2019; Morgan et al. , 2011; Ouarda; Charron, 2018; Ouarda Taha et al. , 2015; Soulouknga et al. , 2018).

Celik (2003) suggested a unimodal distribution; Carta and Ramírez (2007) made use of the bimodal distribution; Ettoumi (2003) proposed a bivariate distribution; and Castino et al. (2003) proposed a hybrid distribution. These and other scholars have addressed the topic using different wind speed variability probability functions.

Some of these studies stand out for having been widely disseminated and used. Among some of these models are the Kappa Distribution, the Weibull distribution and the Rayleigh distribution.

The description of these studies will be presented below, highlighting the most important aspects, in a summarized way.

- Kappa distribution with four parameters (Kappa)

The Kappa distribution with four parameters is a generalization of other distributions and includes as special cases the Generalized Logistic distributions, Generalized Extreme Value and Generalized Pareto (Morgan et al., 2011). The Function Probability Density Function (PDF) and Cumulative Distribution Function (CDF) correspond to Equations (II) and (III).

Equation II – Probability Density Function (PDF)

$$\square(\square, \square, \square, \square 1, \square 2) = \frac{1}{\square}\left[1 - \frac{\square 1 (\square - \square)}{\square}\right]^{\frac{1}{\square 1 - 1}} [\square (\square)]^{1-\square 2}$$

Equation III – Cumulative Distribution Function (CDF)

$$\square(\square, \square, \square, \square 1, \square 2) = \left\{1 - \square 2\left[1 - \frac{\square 1 (\square - \square)}{\square}\right]^{\frac{1}{\square 1}}\right\}^{\frac{1}{\square 2}}$$

Being:

v = wind speed (m/s^2)
c = scale factor (c > 0)
k 1 and k 2 = shape factors (k 1 > 0)
μ = location factor (μ = 0 for a three-parameter distribution)
If k 1 > 0, v has an upper limit at μ + c k 1 ;
If $k_1 \leq 0$, v is unlimited superiorly;
If k 2 > 0, v has a lower limit at $\mu + c\,(1 - k_2^{-k_1}) / k_1$;
If $k_1 < 0$ and $k_2 \leq 0$, v has a lower limit at μ + c / k 1 ;
If $k_1 \geq 0$ and $k_2 \leq 0$, v has a lower limit at $-\infty$

- Weibull Probability Distribution (Weibull)

The Weibull distribution is a statistical model represented by a function biparametric called function F (v) probability density that indicates the probability of occurrence of a given wind speed value (Weibull; Sweden, 1951).

To estimate the wind potential of various regions of the world, the Weibull distribution is recommended for use in situations where there are quantities with variations considerable and for having been validated by several researchers, even if not capable of represent all wind regimes (Shin et al., 2016). The Weibull diagram, which represents statistically the wind probability density distribution is frequently used because in addition to including extreme wind behavior, it can also describe various behavior patterns of it satisfactorily.

The use of the Weibull distribution has the validation of its parameters by the method of least squares, by the method of likelihood, of energy pattern factor, by the empirical method or by the method of moments (DEEP, 2020). There is also the Method of Average Speed and Standard Deviation, considered the most accurate by Araújo (1989), whose equations are presented below:

Equation IV – Average Speed (v)

$$\square = \int \square\ \square\ \square(\square)\square\square$$

Equation V – Wind standard deviation

$$\square^{2} = \overset{\infty}{\underset{0}{\square}}(\square-\square \qquad)\ \square(\square)\square$$

And, in this direction, as an example of the use of this distribution, we can cite the study of Oliveira et al. (2011), on the coast of Northeast Brazil, where, due to the geographical arrangement, the trade winds with characteristics of constancy and intensity, resulted in good conditions for exploration, however, it needed a behavioral assessment, in which it made use of the Weibull distribution, due to the seasonal and interannual climatic variability observed in that region.

In applying the Weibull distribution, to estimate the actual wind power available for the wind turbine, two components of the availability factor must be found, as described by Deep (2020), from the Weibull distribution, father of two parameters (location parameter equal to 0).

The mathematical formula that represents the probability density function of the Weibull distribution, also called Probability of occurrence of the speed of the wind, is described by the expression of equation VI. Equation VII represents the frequency of cumulative probability of the Weibull distribution.

Equation VI – Two-Parameter Weibull Distribution

$$\square(\square) = (\frac{\square}{\square})(\frac{\square}{\square})^{\square-1} \exp[-(\frac{\square}{\square})^{\square}]$$

Being:

p (v) – Probability Frequency of Wind Speed Occurrence V

□ – scale factor in wind speed units (m/s ^{2})

k – shape factor (dimensionless)

Equation VII – Cumulative Probability Frequency of the Weibull Distribution

$$\square(\square) = \square - \square\square\square\,[-(\frac{\square}{\square})^{\square}]$$

Being:

P (v) – Cumulative Probability Frequency of the Weibull distribution

The use of this distribution can be applied to a series of speed data collected in the field, or even in public databases, used to estimate the wind speed at sea and the definition of appropriate areas for the deployment of parks offshore wind farms. Among the most used databases are: International Renewable Energy Agency (IRENA) – DTU Global Wind Atlas database; Energy Research Center Electric (CEPEL) – CEPEL 2013 database; European Center for Medium Range Weather Forecast Time (ECMWF) – ERA5 base; National Centers for Environmental Prediction (NCEP) – base ETOPO; PNBOIA and National Buoy Program and Matrix Forecasting and Research Project Anchored in the Tropical Atlantic (PIRATAS).

Considering the aforementioned Weibull distribution model, several studies are found in the literature for calculating the scale and shape factors included in the equation of Weibull, among which are Kidmo et al. (2015); Mohammadi et al. (2016); Usta (2016). In this line of evolution is the work of Silva et al. (2021) who applied different methods of determining these factors: graphic (MG), Justus empirical (MEJ) and Lysen empirical (MEL), standard energy factor (MFPE), maximum likelihood (MMV) and maximum modified likelihood (MMVM). The aforementioned study found the greatest effectiveness in the method of maximum likelihood (MMV), applying the values of parameters c and k for a series of data collected, with a speed of 8.5 m/s measured at a height of 100 meters, obtained through the Harvester 2 MW turbine.

The scale factor c is responsible for adjusting the magnitude of the function p(V). Already the dimensionless shape parameter k is the change in the peak of the function p(V), that is, it determines the width of the data distribution graph, reflecting which probability peaks per speed ranges that the distribution can assume (Gomes, 2018).

- Rayleigh distribution

This distribution model was originally obtained by the British physicist Lord Rayleigh. The Rayleigh distribution of a parameter is a particular case of the distribution of Weibull when the shape parameter (kW) is equal to 2 (Hoxha et al., 2018). This distribution is uniform and with a precise ability to define wind regimes, being used in many studies to assess wind potential in various locations around the world (Sohoni, et al. , 2016; Bidaoui et al., 2019). It is the simplest distribution as it has a single parameter in its model, with Equation VI being the probability density function (PDF) presented below.

Equation VIII – Rayleigh Wind Probability Density Function (PDF)

$$p(V, c) = \left(\frac{V}{c^2}\right) \exp\left[-\left(\frac{1V^2}{2c^2}\right)\right]$$

Being:

c - Scale factor in wind speed units

k - Dimensionless shape factor

V - Random wind speed variable

For □ □0 □ c ≥ 0we have the factor □ estimated by equation VII described below.

Equation IX - Scale Parameter Estimate

$$c = \left(\frac{1}{2n}\sum_{i=1}^{n} V_i^{2}\right)^{\frac{1}{2}}$$

2.5.3 Power generation in an Offshore Wind System

There are several methods to produce energy with frequency and voltage output constants in a wind turbine. Johnson (2001) presents eight methods, which are

are presented described in Table 3 called Methods of generating electrical energy Synchronous. According to the same author, in each case, the output of the energy collection system wind is in parallel or in sync with the utility system and, specifically, applied to a horizontal axis propeller turbine with two or three blades.

The Johnson (2001) study describes that one method may be unfeasible for certain application, but viable for another and, for this reason, it is necessary to examine several production methods in a wind turbine, so that the choice is achieved of efficient way.

Table 3 – Methods of synchronous electrical energy generation

	Rotor	Transmission	Generator
1	Variable step, Constant speed	Gear of fixed ratio	current generator alternating (AC)
2	Variable step, Constant speed	Gear of two speeds	current generator alternating (AC)
3	Fixed step, Constant speed	Gear of fixed ratio	current generator alternating (AC)
4	Fixed step, variable speed	Gear of fixed ratio	DC generator/ DC motor/AC generator
5	Fixed step, Variable speed	Gear of fixed ratio	AC generator/rectifier/ DC motor/AC generator
6	Fixed step, Variable speed	Gear of fixed ratio	generator/rectifier/ AC inverter
7	Fixed step, Variable speed	Gear of fixed ratio	modulated generator in field
8	Fixed step	Variable ratio	AC generator

Source: Adapted from Johnson (2001).

Johnson (2001) points out that the evaluation of the systems presented considers the differences between its elements and what can be obtained as a result of its implementation. The wind turbines developed over the years have shown evolutions in their structures, however, according to Johnson et al. (2001), the problem persists with the capital cost that is presents high in all models developed over the years. As described by Gonçalves (2022), the competitiveness of plants also depends on the allocation of these costs, which varies according to the country. In some cases, transmission assets are owned by the owner of the national or regional transmission grid and, in other cases, such costs must be incorporated by the offshore, further increasing the cost of energy.

Regarding the equipment that makes up an offshore park, its onerous nature, is reflected in the overall investment, and thus, the cost of an offshore park can be reduced as technology and its size increase. Furthermore, the minimum size of a park should be at least 100 generators with a peak production of 20MW, since such components can promote significant changes in projects.

The use of offshore wind energy to replace a base load electricity generation system with fossil fuels is an important focus of study, given that most of the utility-scale energy storage existing in the world is pumped hydroelectric storage.

2.5.4 Offshore wind energy deployment

According to a study by Denholm (2006), the deployment of wind energy on a large scale can be done through the combination of wind turbine generation with energy storage and long-distance transmission. This statement stems, according to the same author, from the fact that large-scale wind deployment is limited by its production intermittency and remote location of high-value wind resources. The aforementioned work describes the application of a generation system called CAES (Compressed Air Energy Storage), which uses a fossil fuel, usually natural gas, and biomass gasification.

The deployment of the offshore system presents barriers to the integration of its three main components identified in the literature, as described by Wiegner et al., (2024), namely: a) electrical cable connections, b) energy storage systems (ESS), c) energy applications for hydrogen.

Terrestrial transmission networks mainly use High Voltage Alternating Current (HVAC), but this technology is not ideal for long distances, such as maritime transfers. Thus, research compared the transmission options in alternating current (AC) and direct current (DC).

Studies such as that of Elliott et al. (2015) indicate that, from a certain distance, offshore transmission becomes economically viable only with High Voltage Direct Current cables (HVDC). Studies that addressed the integration barriers of the offshore system, , mainly with regard to connecting electrical cables, have been carried out extensively and found the high cost of offshore electricity transmission, especially the increase additional cost for DC transmission compared to AC transmission (Andersen, 2014; Babarit et al. , 2018; Gondal; Masood, 2019).

In this context, there is also the barrier of the unavailability of equipment for fault protection for HVDC networks in mesh, on an industrial scale (Jovcic; Taherbaneh; Taisne; Nquefeu, 2015). Furthermore, there is very little experience with HVDC networks in mesh, with point-to-point HVDC lines being more common (Carrizosa et al. , 2014; Elliott; Bell; Finney; Adapa; Yu et al. , 2016).

With regard to energy storage, Denholm's (2006) research is an example of CAES application. CAES is a hybrid generation and storage system based on the combustion of compressed air, using fossil fuels. The

wind/CAES system presented a natural gas consumption about 85% lower than a generator of combined cycle gas turbine operating with 50% thermal efficiency, and eliminated problems associated with wind intermittency (Denholm, 2006).

On the other hand, the economic aspects resulting from the adoption of each component of the wind system, considering technologies and innovations in this segment, allows evaluating combinations that promote the best allocation of preference for this matrix, resulting in a more efficient utility curve and, consequently, a utility model that can synthesize the benefits of the combination of variables.

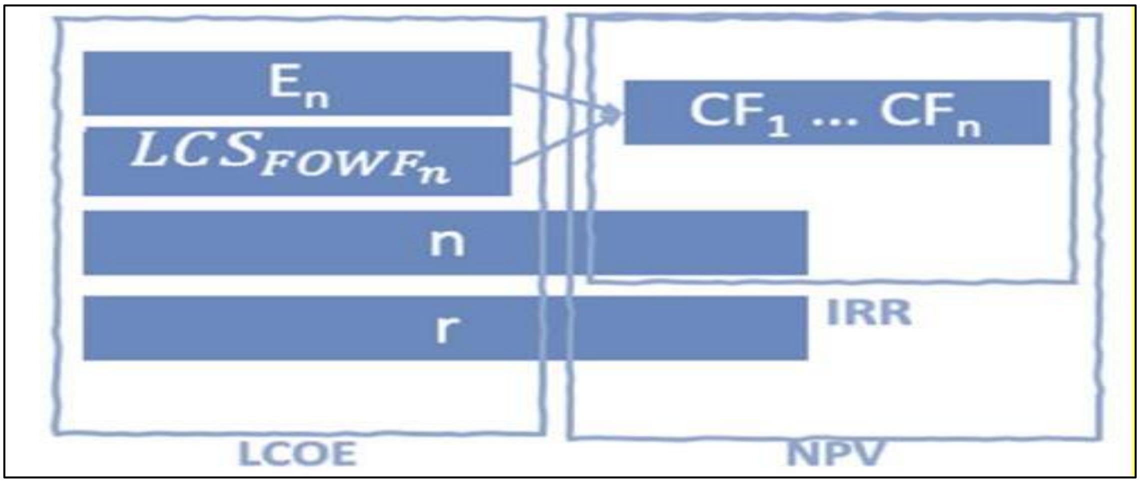
This context complements the evaluations from models and their respective components with economic-financial fundamentals that influence the costs of implementation of this type of project, which over time show growth in its installed capacity with the implementation of parks with turbines of greater power, in areas further from the coast, deeper. This statement can be proven through publications about the growth of this variable.

Studies carried out by Ioannou et al. (2018) reinforced influences recorded in the Capital Expenditures (CAPEX), Operating Expenses (OPEX) and Levelized Cost of Energy (LCOE), when changing the set of variables linked to the implementation of offshore parks. The referred study described that the capacity of wind turbines had an effect of inverse exponential reduction in the three costs: CAPEX, OPEX and LCOE, due to the fact that fewer turbine units are installed and maintained, resulting in cost reduction and increased expected energy production.

It was also found that the increase in water depth resulted in an increase almost linear in CAPEX and LCOE, mainly due to the additional cost of the foundation and support structure, as well as installation, but did not affect OPEX.

Still in this context, the main calculation metrics for the economic evaluation of a wind farm refer to the Net Present Value, Internal Rate of Return, and Levelized Cost of Energy (Net Present Value - NPV, Internal Rate of Return (IRR), Levelized Cost of Energy – LCOE). Based on global decision variables, the relationship between these parameters of economic viability is represented by Figure 14 (Castro-Santos et al., 2014).

Figure 14 – Relationship between economic viability parameters



Source: Castro-Santos et al. (2024).
Notes: En – Input; CF1..CFn - cash flow; LCOE - Levelized Cost of Energy;
IRR - Internal Rate of Ret NPV - Net Present Value; n – time; r – rate.

Given the relevance of these variables, with regard to the economic aspect, the importance of the viability of offshore systems, aligned with social and environmental issues, is evident.

2.6 Viability of an offshore wind system

The standard economic model of an offshore wind system must include characteristics, technical components, in order to carry out a feasibility analysis from that point economic. This is because there are variables that influence the unit cost of electricity, being included in the operating cost and total capital investment. Thus, for the evaluation of viability, it is necessary to list the elements of a wind farm, in order to verify the form to reduce the costs of these projects.

In order to reduce costs, several studies, such as that carried out by Johnson (2001), who published, through previous studies, the comparison between the values of three models of turbine with significant cost reductions in projects with variation: in rotor diameter (m); in nominal power (kw); in nominal wind speed (m/s) and in production quantity.

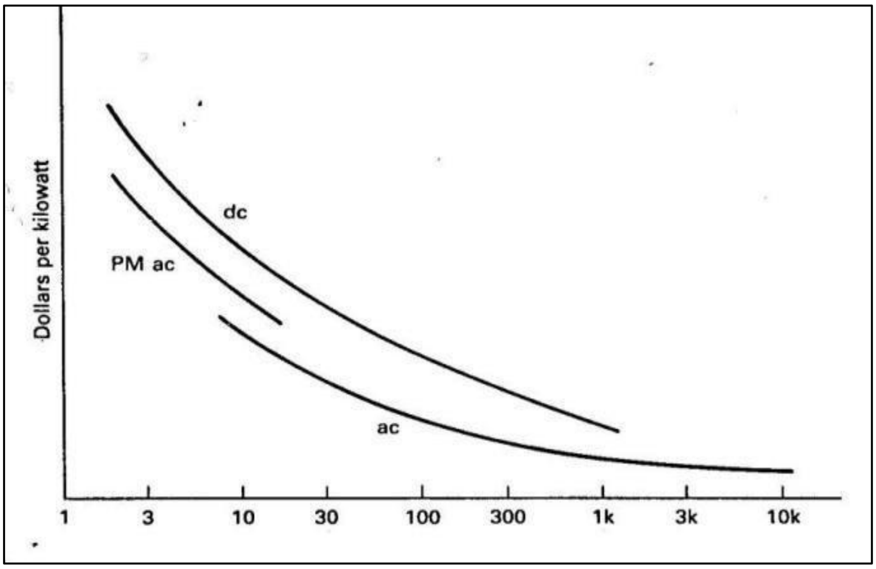
The analyzed components are described in Table 4. The same author highlighted, also, that construction costs per unit of capacity tend to decrease as capacity increases. The behavior of these costs is presented graphically in Figure 15.

Table 4 – Costs considered in the construction of large Wind Turbines

Evaluated items	
Blades (%)	Electric generator and installation (%)
Hub, blade supports, blade rods, bearings, main shaft, nacelle (%)	Control equipment for speed, yaw and load (%)
Tower (%)	Foundations and local work (%)
Gearbox (%)	Engineering (%)

Source: Adapted from Johnson (2001).

Figure 15 – Relative costs of electrical machines



Source: Adapted from Johnson (2001).

Studies carried out by Johnson (2001) show that the overall cost per technology of onshore and offshore wind farms showed significant reductions compared to other renewable energy sources, as can be seen in Table 5.

Table 5 – Total Installation Cost (2010 and 2023)

	Total Installed Cost (2023 USD/kW)		
	2010	2023	% Change
Bioenergy	3 010	2 730	- 9 %
Thermal	3 011	4 589	52%

Hydroelectric	1 459	2 806	92%
Solar	5 310	758	- 86 %
Onshore	2 272	1 160	- 49%
Offshore	5 409	2 800	- 48

Source: Johnson (2001).

Regarding the wind turbine, its cost can be described in four ways, referred to as: Total Cost; Cost per unit area (Equation X); Cost per kW of power (Equation XI), which is widely used; and Unit Cost of electricity (Equation XII). In accordance with Johnson's economic model (2001), the main variables that make up these equations are presented below.

Equation X – Cost per unit area

$$□_{□} = \left(\frac{□_{□}}{□}\right)$$

Where:

C_a –cost per unit area ($/m^{2})

Ct – total cost ($)

A - designed turbine area (m^{2}).

Equation XI – Cost per kW of power

$$□_{□□} = \left(\frac{□_{□}}{□\ □□}\right)$$

Being:

C_{kW} – cost per kW of power ($/kW)

C_t – total cost

P_{eR} – maximum or nominal electrical power of the wind turbine

The unit cost of electricity is the value composed of the cost of generation, transmission and distribution, charges and taxes, and profit margin of the concessionaires. Increase the energy efficiency and modernize the energy distribution system are strategies that provide a reduction in unit cost.

Equation XII – Unit Cost of Electricity

$$\square_{\square} = \left(\frac{\square_{\square}}{\square}\right)$$

Being:

Cu – unit cost of electricity ($/kWh)
An – annual cost of kWh of electricity (not area A)
W – net electrical energy produced per year per kW of power

It is worth mentioning that W can represent the cost of busbar, wholesale or retail. Busbar would be the cost at the generating plant without including transmission and distribution costs. Wholesale would be the price for another electric power utility, including the costs of transmission. Retail would be the price for a certain class of customer according to recommendation of the regulatory agency, and that may not exactly reflect the costs of production. In this description, W represents the busbar cost (Johnson, 2001).

2.6.1 The Levelized Cost of Energy (LCOE)

According to Liang et al. (2021), a clear understanding of the cost-benefit ratio and feasibility of offshore energy technologies is of utmost importance. And the levelized cost of energy (LCOE) serves as a reference for making decisions since its calculation methodology models all aspects to assess the relationship of different energy generation technologies.

In addition, the widely used approach to calculate the cost of onshore projects and offshore involves the optimization of a multidisciplinary project whose main objective is to reduce the LCOE and the focus is progressively shifting from the single machine level to the level of wind farm, whose environment where the project is located offers more optimization flexibility of the layout, aiming at the combination of cost functions capable of capturing turbine interactions with sufficient accuracy and adaptable to any deployment site (Yilmazlar et al., 2022).

The levelized cost of energy (LCOE) defined in the study by Yilmazlar et al. (2022) of the entire wind farm is calculated including CAPEX (capital expenditures), AOE (Annual Expenses Operational) and AEP (Annual Energy Production). From this perspective, the calculation carried out in this study considers types, turbine dimensions and site characteristics, as well as the cost uncertainties found in the different types of offshore cost modeling.

This metric represents the present value of the price of electricity produced, over the life of the plant, considering the costs of construction, operation, maintenance and decommissioning. LCOE is a measure that represents the total cost of generation of electricity considering all investments and expenses of operation and maintenance, divided by the total amount of electricity generated over the entire life of the system.

The general formula for calculating LCOE is:

Equation XIII – General Formula for LCOE

$$□□□□ = \frac{□_{□□□□□}}{□\ □□□□□}$$

Where:

C total is the total cost of the project (including the costs of capital, operation and maintenance, and other costs over the life of the project).

E total is the total amount of energy generated over the life of the system.

The LCOE, therefore, reflects the cost per unit of energy (usually expressed in R$/MWh, or USD/MWh, or R$ /kWh or USD/kWh), considering the temporal distribution of costs and energy production over time.

In turn, in the study carried out by Aldersey-Williams and Rubert (2019), the calculation of LCOE is done through two main methods: one suggested by the Department for Business, Energy and Industrial Strategy – BEIS and which dominates the United Kingdom; and another suggested by the Department of Energy's National

Industrial Strategy) and which dominates the United Kingdom; and another suggested by the Department of Energy's National Renewable Energy Laboratory – NREL of the

USA. The first defines LCOE as "the discounted cost of ownership and use of an asset of generation, during its useful life, converted into an equivalent unit of generation cost in £/MWh" whose formula is presented by Equation (XIV). In this case, the LCOE divides the sum discounted costs by the discounted sum of energy production.

Equation XIV – Levelized Cost of Energy (LCOE BEIS)

$$□□□□\ □□□□ = \frac{□□□\ □□□□}{□□□} = \sum_{□=1}^{□} \frac{□_{□} + □_{□} + □_{□}}{(1+□)^{□}} \Big/ \sum_{□=1}^{□} \frac{□\ □}{(1+□)^{□}}$$

With:

NPV cost =Net present value of costs

NPE = Net Present Energy

E_t = Energy generated in period t

t = period from year 1 to year n;

C_t = cost of capital in period t (including decommissioning);

O_t = Fixed operating cost in period t (including fuel cost, carbon costs and sometimes taxes, etc.);

V_t = Variable operating cost in period t

d = discount rate

n = last year of operation

Applying the theoretical concept that when the NPV of a project is zero, the internal rate of return (IRR) of the project is equal to the discount rate, the NPV revenues = NPV costs then the equation XIV can be written in terms of revenue per unit of energy, and this makes it clear that LCOE BEIS reflects the minimum real price required for the project.

The second calculation method, adopted by the USA, defines the LCOE in terms of cost annual energy where the cost of capital includes the capital recovery factor (CRF) with based on the cost of financing the capital for the project, called LCOE NREL and calculated by Equation (XV). This method calculates the total costs over an annual period and divides by the energy generated in the same period. Thus, the LCOE NREL is the required price of energy so that the project exactly meets its operating costs in a year and the portion of costs of capital (including the financing costs of these costs) in that year (Aldersey-Williams; Rubert, 2019).

Equation XV – Levelized Cost of Energy (LCOE NREL)

$$LCOE_{NREL} = \frac{C_O * CRF + \acute{O}}{8760 * FC} + f * h + V$$

With:

C_O = Overnight capital cost;

FC = capacity factor;

f = fuel cost;

h = heat rate;

V = variable cost of operation;

Ó = fixed operating cost;

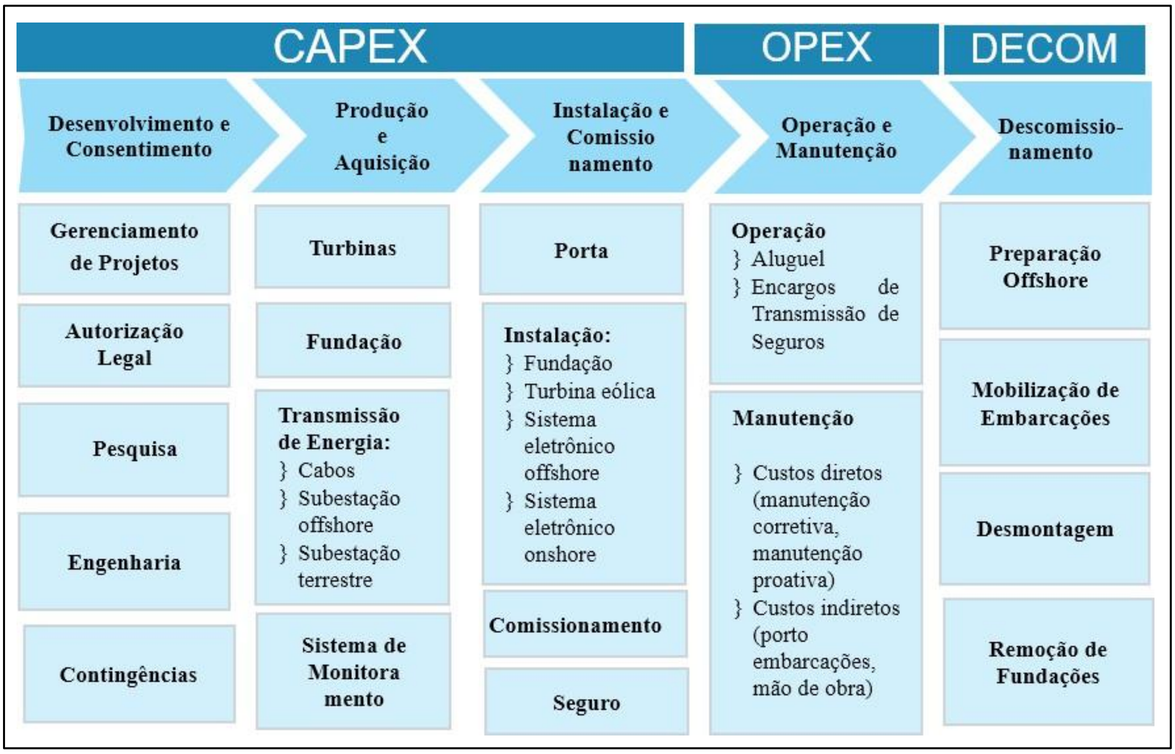
CRF = capital recovery factor = $\frac{i(1+i)^n}{(1+i)^n - 1}$

n = number of payments made to repay the capital; i = interest rate;

Within the scope of this cost metric, the approach taken by Bosch et al. (2019) highlights the fact that the capital costs of offshore energy depend on specific conditions, in addition to wind, such as distance to the grid infrastructure (cost of transmission lines); foundation depth (suitable foundation technology); and weather conditions that affect energy availability and installation and maintenance strategies.

The same study described the cost factors considered in an offshore wind project and the temporality of each of the components of this cost, in a schedule, described in Figure 16, presented below.

Figure 16 – Summary of life cycle costs of an offshore wind farm



Source: Adapted from Bosch et al. (2019).

As shown in Figure 15, capital costs (CAPEX) and operating costs and maintenance (OPEX) are paid over different phases of the wind farm's life; the decommissioning costs (DECOM) are financed in advance as part of the CAPEX, but in the wind farm timeline they appear at the end of life Categories of Renewable Energy (Bosch et al. , 2019).

The differences in LCOE applications, which are often determined by data availability and research objectives, show that the tool is adjustable to specific conditions (Foster et al. , 2014). Examples of cost models implemented for a specific location and turbine project are reported in the literature. In addition, several projects substructure are compared for different installation locations, and which provide methods of scalable cost modeling for wind farm calculation (Yilmazlar et al., 2022).

It can also be defined by the revenue required to obtain a rate of return of investment equal to the weighted average cost of capital (WACC) considering the useful life of the system.

In line with this importance, Table 6 presents the behavior of this parameter in several places in the world, where the offshore wind energy matrix stands out, since 2010.

Table 6 – Weighted average LCOE of offshore wind energy, 2010 and 2023

LCOE (2022 USD/kWh)	**2010**	**2023**
Offshore wind	Weighted average (2023 USD/kWh)	
Asia	0,197	0,078
China	0,197	0,070
Japan	0,207	0,211
Republic of Korea*	n.a.	0,195
Europe	0,205	0,067
Belgium*	0,244	0,090
Denmark	0,117	0,048
Germany	0,195	0,063
Netherlands**	n.a.	0,061
United Kingdom	0,224	0,059

Source: Adapted from GWR 2024-Digital-version-final-1.

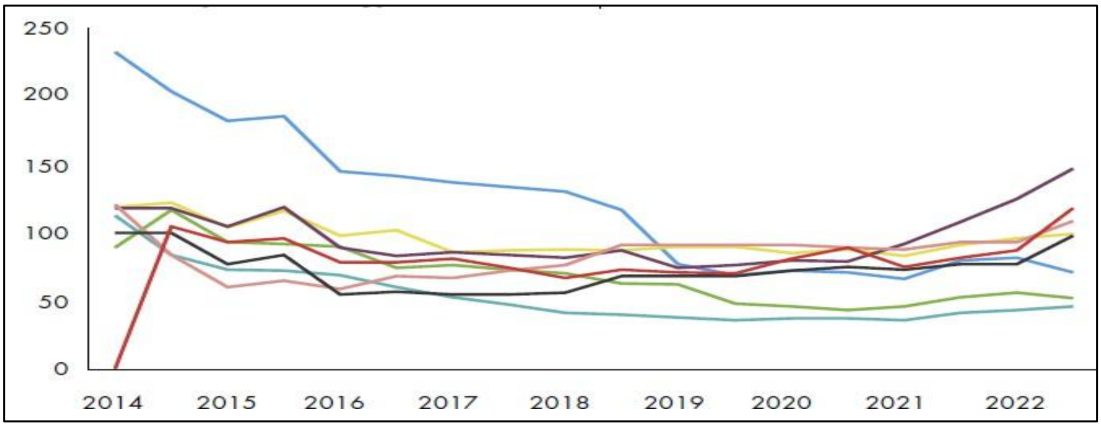
Considering this line of reasoning, the work of Aldersey-Williams et al. (2019) describes that this metric adds up the life cycle costs of the energy system in consideration (such as a wind farm or a CCGT plant) and divides by the energy production over the life cycle to provide a result in cost per unit of energy.

The value of the levelized cost of energy (LCOE) is one of the important parameters for assess the potential of the project. In the case of offshore farms, this variable has great influence on the budget of this investment and, according to the interpretation of the LCOE, it can be the cost required to produce electricity during the project's life cycle (Dinh, 2023).

Hou et al. (2019) carried out a study where a mathematical model was proposed to optimize the location of wind turbines in large-scale parks, considering the variation of wind direction and wake deficit. The study applied an optimization algorithm by particle examination, using LCOE as an objective function, in a practical case in Germany, generating greater efficiency and cost reduction.

The UK government was the first to propose cost reduction targets, back in 2012, and achieved a 63% drop in offshore energy costs (RSTED, 2019). Suitable operational choices considering the evolution of the Levelized Cost of Electricity – LCOE) have allowed for greater economic attractiveness of this energy source, due to the fact that this parameter presents a decreasing behavior over time, as reported by GWEC (2023), through a study on offshore investment in the United Kingdom comparing this source to other sources of energy generation, as represented by the graph in Figure 17, below:

Figure 17 – Historical behavior of LCOE by technology in USD/MWh



Source: GWEC (2023).

Legend:

● US onshore wind UK onshore ● wind US Coal ●
●UK Offshore Energy CCGT in the ● UK Japan Coal ●
●Philippines Coal Combined Cycle ● Gas Turbine (CCGT) Japan

Among the works that point out guidelines for the implementation of offshore parks are the following studies: Kong et al. (2021), who emphasized the importance of coastal management through emphasis on training, political will and sources for financing these enterprises; Medeiros (2020), which found that territorial development sustainable must be associated with the political dimensions of environmental conservation, awareness socio-environmental, circular economy, focus on the sustainability of global governance, and focus on sustainability of global spatial planning; the study by Arabzadeh et al. (2020), which describe the use of offshore energy as one of the vectors of energy optimization in macro scale in urban systems; Igwemezie, Mehmanparast and Kolios (2019), who delved into in researching ways to reduce costs in the factors of the offshore project; and, lastly, can to be cited is the study by Marugán et al. (2022), which creates a technical-economic model to quantify and reduce conflicts in outsourced maintenance services for wind farms offshore, among others.

It is important to consider the bottleneck that refers to cost. Financial circumstances presented themselves favorably in the cost of these projects, which, according to Wood analysts Mackenzie, from 2015 to 2020, demonstrated a 50% reduction. Furthermore, throughout the world, consistent support policies are being developed, highlighting the United Kingdom, Germany, Denmark, and China.

In the national case, the importance of deepening studies on the feasibility economic-financial of this energy matrix is justified by the following factors: need to increasingly diversify the national energy matrix in order to compose a percentage greater in renewable resources; political interest in this matrix, evidenced by the publication of Decree No. 10,946, of July 15, 2022, which fills a regulatory gap for generation of offshore energy; reduction of costs in offshore wind projects, which allows feasibility analysis, making such projects attractive; expansion of the use of this source for complementarity of the use of other energies, such as green hydrogen and systems of storage; and, last but not least, increased access to electricity both to maximize social benefit and to the growing demand for operations that require clean energy, with consequent sustainable benefits for the planet.

In this direction, the proper management of wind resources is important and can be implemented through four aspects, according to studies by Smith (2007), namely: interconnection of wind farms, operational impacts caused by this system, transmission planning, and, lastly, market operation issues and accommodation of the increasing amount of energy. Therefore, there is a preponderance of studies focusing on the expansion of electricity generation with guidelines aimed at reducing costs, which is the most commonly adopted worldwide.

In this context, studies involving LCOE were carried out by Ozato et al. (2023), Santa Catarina (2022), Levitt et al. (2011), Maienza et al. (2020), Stehly et al. (2020), Bilgili et al. (2023), among others, evidencing, then, the growing search for the best result for offshore energy systems.

2.7 Optimizing the utility of offshore wind farms

The complexity of offshore complexes is presented in the project itself due to the onerous nature and the need to complement these systems with other non-wind generation due to service maintenance during periods of less intense winds. This aspect can be assessed with the adoption of new technologies and studies on the quality of winds, measured by specific parameters, such as the capacity factor in areas of interest, which may increase when these projects are further away from the sea coast, as this parameter is calculated by the ratio between the effective production of the park and the maximum power installed for the same period of time.

Nogueira (2020), analyzing the aspect of complementarity of resources in Brazil, determined, through the application of Pearson's Correlation Coefficient (r), the Degree of complementarity of energy resources in coastal regions of the country and by different sources. In this study, results of the behavior of the combination of offshore source with source: hydroelectric; onshore; solar and thermoelectric. Furthermore, given the size of the country's hydroelectric park, the analysis was divided into the four national subsystems (Northeast, South, Southeast/Midwest and North) and found satisfactory results in the performance of these regions, with emphasis on the Northeast and Southeast, which presented more favorable points for the installation of offshore parks. This work found the need for more studies technical, economic, socio-environmental, as well as regulatory improvement in order to allow the greater use of this energy source for the national energy system.

The transmission of bulk wind energy from potentially high regions to regions with greater energy deficiency using offshore energy to employ on land, voltage source converter topology and a submarine cable system appears to be a strategy of viable alternative transmission; and if the transmission route can be chosen from distances close to the coasts, the cost can be reduced (ABEEÓLICA, 2023). This dizzying increase in licensing of offshore parks places wind energy in prominent position in the electricity concessionaire system and directs the management of wind resources to a strategic operating position.

The management of wind resources, according to studies by Smith et al. (2007), emphasizes four main sessions (aspects), namely:

- the interconnection of plants that considers the aspects of complementarity already reported previously, synchronized and with damped oscillations;
- the operational impacts, which concerns the physical impacts of wind on the network of distribution and resulting costs; transmission planning and operations of

allocation of imbalance costs for power generation, which, in this study, is treated in light of optimizing a cost system and economic considerations; finally,

- the importance of quantifying utility systems and means of expanding the transmission system, in addition to aggregating and expanding production in various geographic regions in order to accommodate the increasing wind penetration of the future.

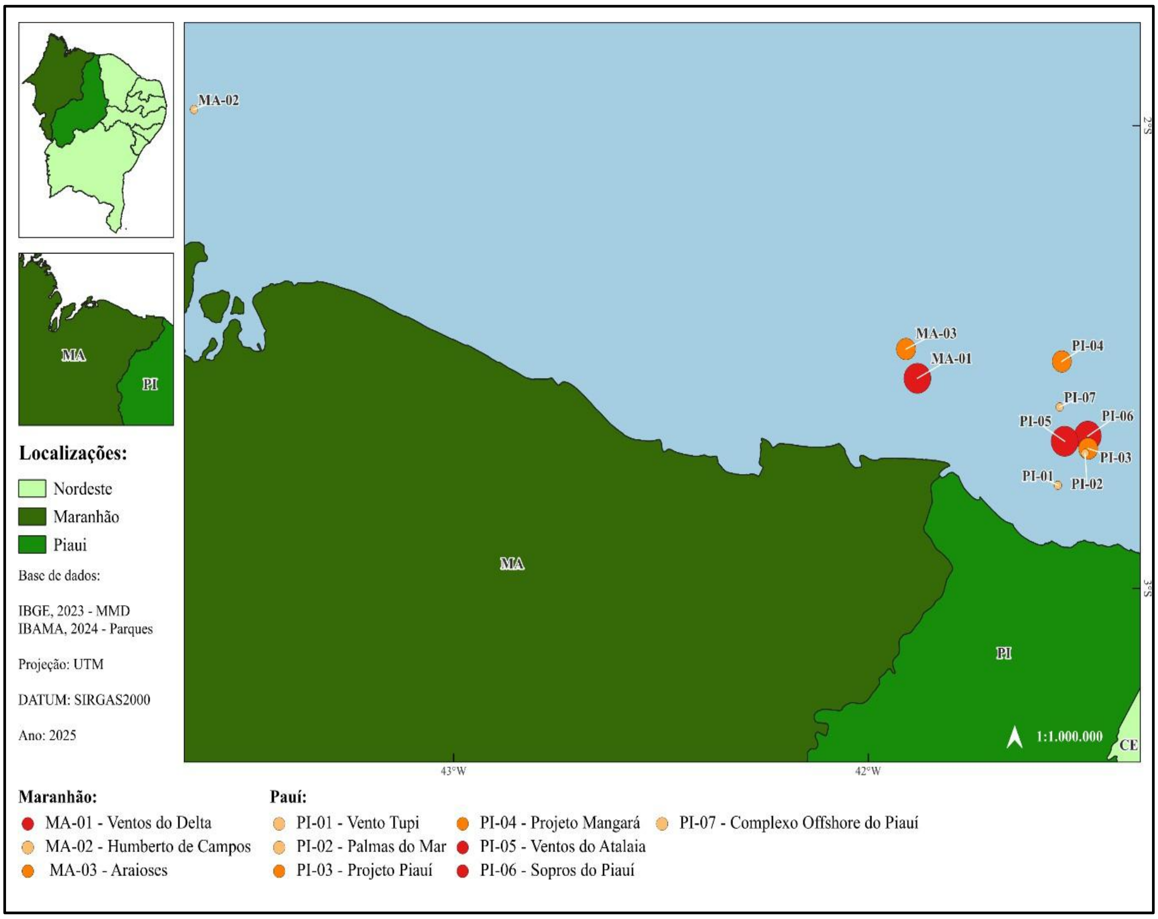
Thus, considerations, studies, and innovation assessments regarding mechanisms for adding aspects not included in the planning models for the optimal expansion of the current power system in offshore wind systems, can bring significant and innovative results to this energy matrix. innovative for this energy matrix.

3- How to discuss wind farms

Offshore wind farms and the proposed assessment of the distribution of parks in the Northeast region took as a criterion the aspect of the area's electricity infrastructure, the expansion of access to energy, and the prospects that the development of this matrix can provide, reducing energy inequality and poverty in the region.

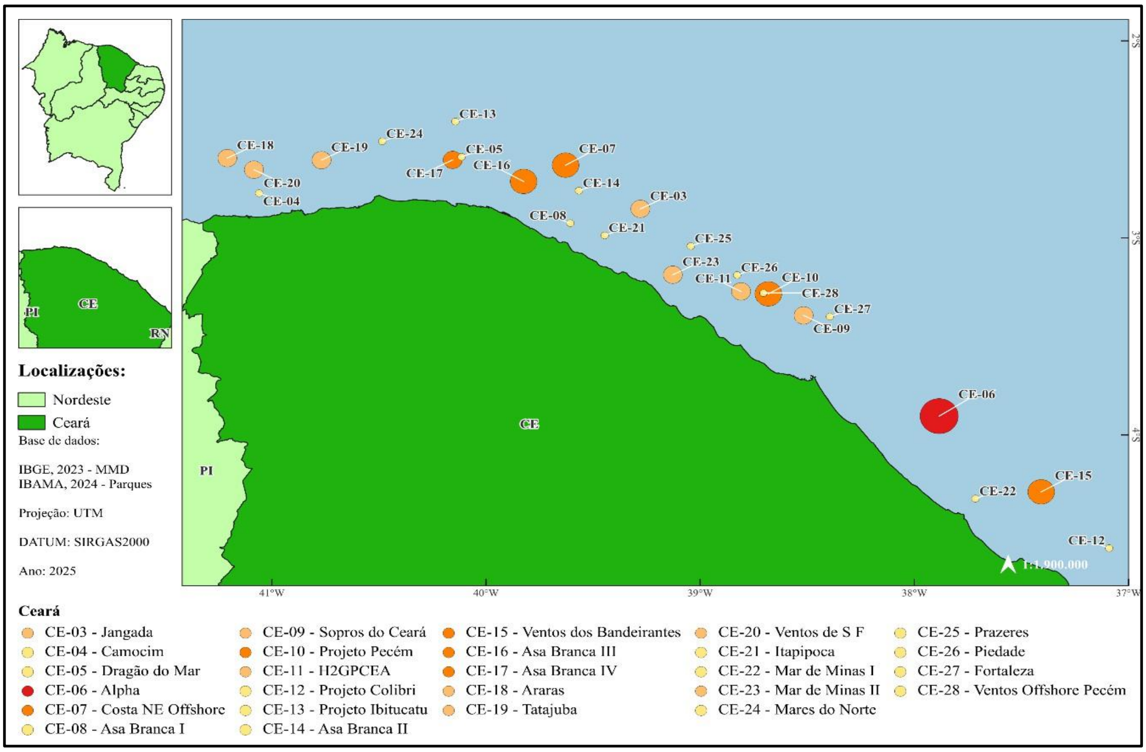
Therefore, in order to achieve the objectives proposed for this work, the research was formed by studies in a global context, where data were collected about variables included in offshore wind energy projects and other specific variables of the 50 offshore wind farms in the process of licensing in the national territory. The parks distributed in the Northeast region are located as shown in Figures 18, 19 and 20.

Figure 18 – Offshore Parks located in Maranhão and Piauí



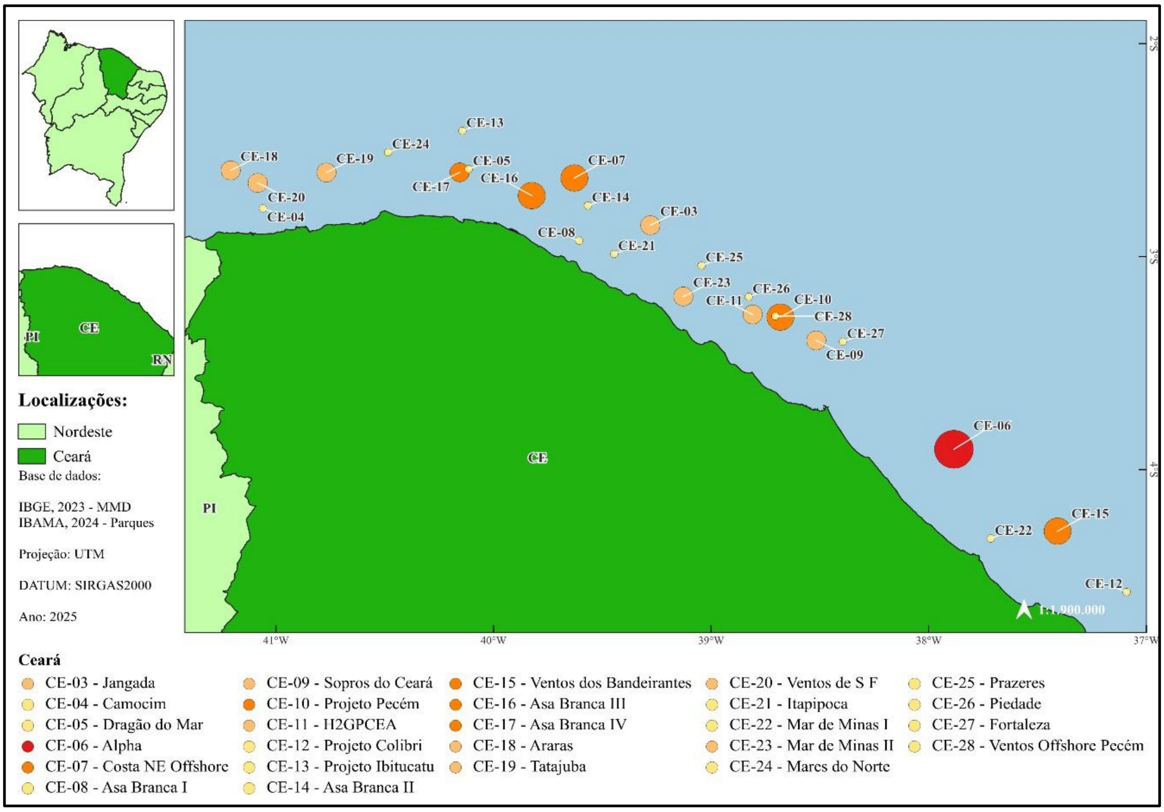
Source: adapted from IBAMA (2024).

Figure 19 – Offshore Wind Farms located in Ceará



Source: adapted from IBAMA (2024).

Figure 20 – Offshore Wind Farms located in Rio Grande do Norte



Source: adapted from IBAMA (2024).

3..1 Model 1

Through bibliographic reviews of the topic addressed, a survey of the historical record of wind energy, onshore and offshore, in terms of representativeness in the world, with the purpose of achieving the outlined objectives, through institutional websites, publications, reports from the energy sector in Brazil and in the world.

Contemplating from ancient to recent periods, the sources of greatest contribution the representative institutions of this approach are listed in Table 8, below presented.

Table 7 – Representative energy institutions

ABEEólica	Brazilian Wind Energy Association
ANEEL	National Electric Energy Agency
CONAMA	National Environment Council
EPE	Energy Research Company
GWEC	Global Wind Energy Council
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
GWA	Global Wind Atlas

Source: Own authorship.

The search for the aforementioned material, in addition to raising evolution and specific data, considering aspects of a global nature, allows studies aimed at decision-making strategic in favor of modernization and innovation of this energy matrix, based on the data raised about onshore and offshore energy, in the world, and in Brazil, more specifically, in the northeast region.

Inferential analysis was applied to a database built in Excel format, version 2024, for the realization of descriptive tables and the application of statistical tests.

In this way, the first stage of the study was carried out to achieve the objective of verify the possible trends observed in the period from 2000 to 2023, among the ten largest wind energy producers in the world; the states of Northeast Brazil and the variables that influence the supply, demand and sustainability of the energy sector, namely: generation of offshore and onshore wind energy in the world and in Brazil; Installed capacity of wind energy offshore and onshore in Brazil and in the world; public investment in offshore wind energy and onshore in Brazil and in the world; generation and installed capacity of energy by region, source and by states in the northeast of the country; and lastly, GHG from energy generation in the country, by type of emission.

In this scenario, statistical inference was used, where the following tests were performed: Shapiro-Wilk; Mann-Kendal; Kruskal-Wallis; and Bonferroni.

Initially, the Shapiro-Wilk test was applied to the study sample. This test statistic is used to verify whether a given data set comes from a normal distribution or not and adopts the following hypotheses, according to Shapiro & Wilk (1965)

H0: The data has a normal distribution.

H1: The data does not have a normal distribution.

Subsequently, the non-parametric Mann-Kendal and Kruskal tests were applied-Wallis, which estimated the average of each variable described and verified the results of trend and evidence of statistical difference between the aforementioned variables.

The Bonferroni test, which is not a non-parametric test, but is a method that adjusts the level of significance found between the pairs of study groups, was applied in pairs of the multiple groups tested in this research, enabling the grouping of results verified in pairs.

The Mann-Kendal and Kruskal-Wallis tests were conducted to determine whether the study variables showed statistically identical behavior in the samples collected and evaluated. This study identified the validity of the null (Ho) and alternative hypotheses (H 1) The validity of the hypotheses was established to determine whether to reject the hypothesis null or not. It is worth mentioning, however, as described by Kwak et al. (2022), that rejecting the null hypothesis proves that the alternative hypothesis is correct. On the other hand, not rejecting the hypothesis null does not prove that the alternative hypothesis is not correct.

The classic Mann-Kendall approach, among other tests, is frequently used to identify potential trends. This test presents statistics determined by the classifications and sequences of time series instead of the original values and is robust when dealing with non-normally distributed data, censored data, and time series with values missing (Hirsch; Slack, 1984).

The Mann-Kendall test is a sequential, robust, and non-parametric method used to verify whether a given data series has a statistically temporal trend significant. Furthermore, as it is a non-parametric method, its application does not require normal distribution of the data (Mann, 1945; Kendall, 1975).

The Kruskal-Wallis test is also a non-parametric test for comparing means which is used as an alternative to the parametric analysis of variance test, when the assumption of normality and homogeneity of the data are not met.

With regard to the statistical significance of the aforementioned tests, the level of acceptable significance of 5% (0.05) was assigned. Thus, if the p value < 0.05, it is considered that there is a significant difference between the variables. If the opposite occurs, that is, the p value > 0.05, it is considered that there is no significant difference (Kawak et al., 2022).

Thus, considering that the null and alternative hypotheses refer to the medians, H 0 : There is no difference between the variables studied. H 1 : There is a difference between the variables studied.

And considering results in which the Kruskal-Wallis test to compare the variables of study, indicates that there is a statistical difference between them, an auxiliary test can be applied, to perform multiple comparison. In the case of this study, the test applied was the Bonferroni test, to avoid that a result is considered significant only by chance; and because Bonferroni , to avoid that a result is considered significant only by chance; and because it is necessary to perform multiple tests simultaneously.

For the final analysis, the results from the application of inferential statistics were obtained through the use of the statistical softwares R and SPSS. The programming software R was applied since through this tool it is possible to integrate the stages of collection, treatment, analysis and presentation of data in a single environment. In addition, R is a language of open programming, whose operation occurs through the installation of free packages (Wooldridge, 2013).

As reported by Lopes (2013), the Statistical Package for Social Sciences (SPSS) is a tool used for data analysis and allows to manipulate, transform, create tables and graphs that summarize the information obtained.

Its potentialities go beyond the descriptive analysis of a set of data. It is possible to perform more advanced procedures with this software such as statistical inference, hypothesis testing and multivariate statistics for qualitative and quantitative data (Lopes et al, 2013). The application of these tests in the study guaranteed a more reliable and robust analysis of the results obtained.

3.2 Model 2

The second part of the study was carried out in order to fulfill the objective of determining a parametric expression of initial cost model for offshore energy parks of

Northeast, through simulations as a function of some independent variables that are included in investments in offshore wind farms.

For this stage of the research, the study carried out by Ioannou et al. (2018), which developed parametric expressions for capital, operational and levelized cost of energy, as a function of the parameters: wind turbine capacity, water depth, distance from port and wind farm capacity. In this study were developed expressions through a series of simulations based on a cost model.

The study carried out in this work developed a model for direct and indirect costs, through the application of multiple regression equations for investments in offshore wind farms in MA, PI, CE and RN considering the values published in the Plan Ten-Year Energy Expansion 2030, in order to achieve relationships between the variables involved in these ventures that are not observed directly and that depend on data from each wind farm studied.

EPE provides, in the Studies of the Ten-Year Energy Expansion Plan 2030, the economic parameters by type of energy offered (Brasil, 2021), which was considered as reference for the estimation of the study carried out only the portion of direct and indirect costs (CAPEX) as it is an investment that has not yet defined the participation of capital from terreiros in the investment (Table 9).

That said, parametric tests necessary for verify the assumptions of the residue of the model adopted in this work, which will be described in the methodology sequence.

Table 8 – Economic parameters by type of energy supply

Type of Offer	Useful life eco-mica [years]	CAPEX ranges, min. and max. [R$/kW]	CAPEX Reference, without IDC [R$/kW]	Average Capacity Factor	O&M [R$/kW/ year]	Charges/ Taxes [R$/kW/ year]	Average Disbursement Time [months]
Wind Onshore	20	3,200 to 5.500	4.500	38% -47%	90	180	24
Wind Offshore	20	9,800 to 18.600	12.250	32% -62%	490	450	36

Source: Adapted from Brasil (2021).

Using statistical methods to estimate the relationship between independent variables, the parameters and the cost, a model can be proposed, considering the assumptions of Regression Multiple linear. Thus, CAPEX, to be described in the regression model adopted, includes all direct costs (civil works, equipment, connection and environment) and indirect costs of the project, with reference to the month of December/2019 (EPE, 2024).

Considering the sample of the 50 parks mentioned above, and even though the wind (and its characteristics of speed, direction, frequency) is the main component of the exploration of the wind resource, the delimitation and operation of wind farms is conditioned to their implementation in areas whose final production also takes into account, in addition to location, bathymetry, the distance from the coast, the depth and the type of soil. Therefore, the production ratio varies according to project data, whose configuration of each region presents as independent variable the Cost (CAPEX), and as independent variables in each park: The Power Pot. Tot (MW), the Park Area -Ap (km²), the Export cable Length L (Km), the Depth - F(km), and the Distance from the Coast D(km).

Therefore, the positions, conditions and specific characteristics of each of the aforementioned parks were collected, then statistical techniques were applied as a purpose to model the CAPEX of the parks included in the sample of this study.

3.3. Model 3

The multiple linear regression model is a statistical model that analyzes the relationship between an outcome variable and multiple predictor variables. It is a procedure that can be used to make future predictions and for this reason will be applied in modeling the cost of energy generation from parks in the northeast region of the country.

The statistical model of a multiple linear regression with k explanatory variables can be represented by the equation, as described by Hoffmann (2016):

Equation XVI – MRLM

$$Y_i = \beta_0 + \beta_2 X_{i2} + \beta_3 X_{i3} + \dots + \beta_k X_{ik} + \varepsilon_i$$

The inference of the parameters is carried out from the application of the method of Least Ordinary Squares - OLS (in English - Ordinary Least Squares), where Y is a variable dependent and X i are the independent variables. The equation (XV) represented above presents the intercept defined by the value of β_0 , the predicted value of y when x is equal to zero.

An alternative to the Least Squares method is the Maximum Likelihood method (MLE). However, to apply this method, it is necessary to make an assumption about the probability distribution of the error term ε_i . In the context of regression, the most common assumption is that ε_i follows a normal distribution (Gujarati, 2008).

Gujarati (2008) defines that the slope of the line equation, in stochastic form, is given by the variable β_0 ,and the equation that represents the factors that take into account the inexact relationships between economic variables, writes an econometric model described by equation XVI above that can also be described in generic form as presented by equation XVII:

Equation XVII – General MLRM

$$Y_i = \beta_0 + \square \beta_i X_{ik} + \varepsilon_i$$

Where:

Y = dependent variable

Y_i = predicted value of Y for a given value of X_i;

X = independent variable;

β_0 = predicted value of Y when $X = 0$;

β_i = how much Y changes, on average, per unit change in X (slope).

In these terms, β_0 represents the intercept, that is, the point on the linear line where Y_i is equal to X_i . The terms β_0 and β_i are called regression coefficients and express the variation of the term Y_i , when X_i undergoes the variation in one unit. And the last term, called stochastic, ε represents the residual of the model, which the study may present when trying to explain the variable Y_i , through the independent variable X_i .

The minimization of the Sum of Squares of the regression residuals allows the maximization of the degree of adjustment of the model to the observed data (Menezes, 2023).

Applying the method to the study proposed by this work, the study variables were defined as follows:

a) Dependent variable: Cost (CAPEX)

b) Independent variables:

Park Area (Ap);	Cable Length (L);
Depth (F);	Distance from the coast (D)

3. 3. 5 The analysis of the assumptions applied in the Multiple Linear Regression

The Assumptions of Multiple Linear Regression are described for the MRLM, thus distributed, according to HAIR, et al (2009):

- * Linear relationship between the independent variables and the dependent variable;
- * Normal or Gaussian distribution behavior;
- * Homoscedasticity – $E(\varepsilon_i^2) = \sigma$; (statistical concept that indicates that the variance of errors is constant in a regression model);
- * Autocorrelation (independence of residuals);
- * Multicollinearity;

The results of the analysis of the assumptions in the application of the Regression Method Multiple Linear (MLR), are presented in graphic format, but are also based on the statistical tests of Breusch-Pagan, Durbin-Watson and Kolmogorov-Smirnov, performed on the residuals of the estimated models.

The Kolmogorov-Smirnov (K-S) test, as well as the Shapiro-Wilk (S-W) test applied in the first stage of the study, aimed to assess whether the distribution of the data approaches a normal distribution (also known as a Gaussian distribution).

Lopes et al (2013) explored the K-S and S-W tests. They showed that the tests mentioned above provide the test value parameter (p-value, p-value or significance), which can be interpreted as a measure of the degree of agreement between the data and the null hypothesis (H_0), being H_0 corresponding to the Normal distribution. The lower the p-value, the lower the consistency between the data and the null hypothesis.

The Breusch-Pagan test can be applied to verify the Homoscedasticity of the residuals. This test presents as a null hypothesis (H_0) the occurrence of Homoscedasticity when the pValue is greater than 5%, discarding the alternative hypothesis H_1 . otherwise, or that is, a p-value less than 5% leads to non-observance of Homoscedasticity, thus discarding the null hypothesis (H 0 (Wooldridge, 2016).

The Durbin-Watson test is applied to verify whether there is independence of the residuals of the model, that is, whether the variables are correlated, and if there is multicollinearity between the independent variables, the estimation of the correlation coefficient will be affected. The matrix of correlation between the variables is also one of the behaviors described in the results.

4 Wind energy generation in the World and in Brazil

For the analysis of wind evolution, it is necessary to extract data referring to installed capacity, generation and investments over the years in the regions that most have developed this energy matrix.

Thus, data on the occurrence of the advancement of energy were listed and analyzed wind power in the global and domestic (Brazilian) context. In addition, the aspects most susceptible to success regarding offshore wind energy in particular were highlighted. Then, in the second stage of the work, a cost estimation model for the parks will be proposed offshore.

Considering that wind energy has consolidated itself as one of the main sources renewables for electricity generation in the world, a fact intensified by the growth of policies with incentives to search for sustainable energy sources, statistical studies have been relevant in this segment. Especially, since the beginning of the 2000s, the installed capacity and the generation of the wind energy matrix have been growing and have become essential pillars in the energy transition process.

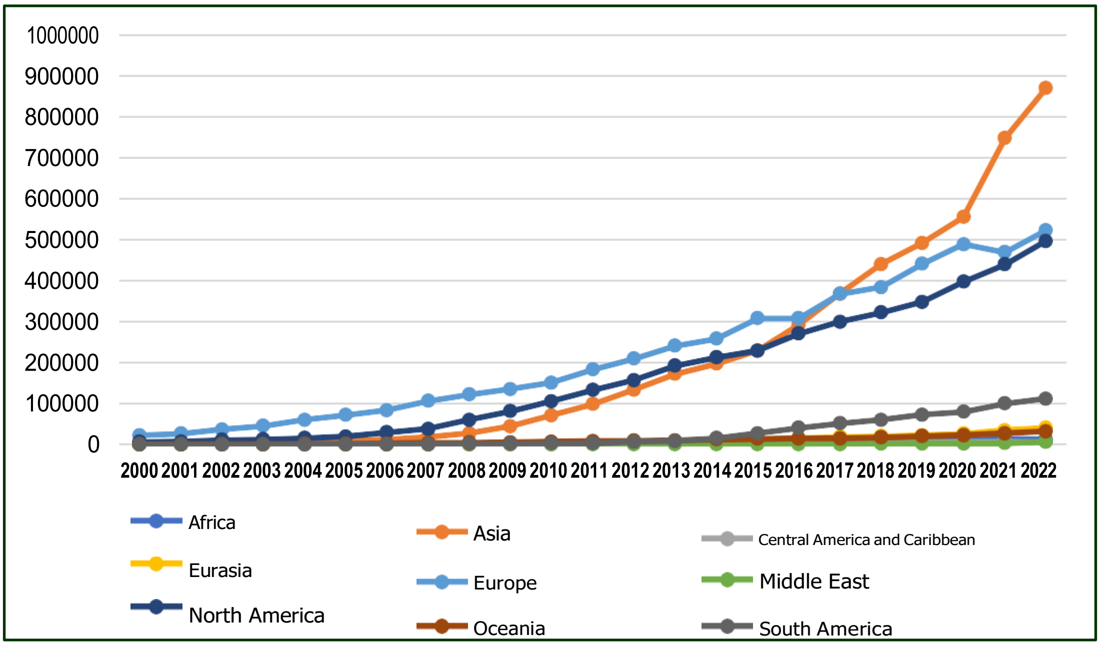
The global panorama reveals, however, trends between the continents, due to factors characteristic of each region, as described in the results of the data analysis presented below. Some regions stand out, leading the development of wind energy, and others are still in the initial process of diversifying the renewable matrix. In order to contribute to the study on the level of association between the global evolution of wind energy and the sectors researched, the Mann-Kendal test and the Kruskal-Wallis test were applied. With this, statistically significant results of trend and statistical differences between the variables studied were obtained. The p-value reflected this probability.

Non-parametric tests, such as the Mann-Kendal test and the Kruskal-Wallis test , refer to the importance of analyzing research data in which the distribution of the population and its parameters are not known. In this case, it is not necessary to admit hypotheses about its distribution or the samples are small.

4.1.1 Wind energy generation in the world

For the analysis of the evolution of the wind matrix, generation data were listed from electricity in the world over the period from 2000 to 2022. During this period, there was a significant growth in wind energy generation in Europe, North America and Asia. The behavior that can be seen in Graph 1, below, also denotes evidence statistics, as described in Table 1, which presents the results achieved through the application of specific statistical tests.

Graph 1 – Wind energy generation in the world (GWh)



Source: Adapted from IRENA (2024).

Thus, assigning a significance level of 5%, using the Mann-Kendall test , there is statistical evidence of a trend, between the years 2000 and 2022, regarding the generation of electricity on all continents. Furthermore, through the Kruskal-Wallis Test, there is evidence of statistical difference in electricity generation between continents. Europe, Asia and North America presented greater electricity generation.

The result of pValue (1) less than 0.05, for the Mann Kendall Test suggests that there is trend regarding wind energy generation in the world. Considering the result obtained for

Following the Kruskal-Wallis test, these differences were observed. The application of the test of Bonferroni was carried out, which allowed the continents to be grouped into groups whose differences significant statistics were evidenced. A combination of factors can be listed for the most expressive result of greater energy generation in the continents of Asia, Europe and North America. These factors can be verified in the geographic, economic, political and technological contexts.

According to the International Energy Agency (IEA, 2024), environmental policies strict – such as the Green Deal and the Kyoto Protocol – encouraged investments in renewable energies, in addition to subsidies, feed-in tariffs and mandatory targets that boosted the growth of wind energy in Europe. This occurred mainly in Germany, Denmark, in the United Kingdom and Ireland. This continent needs to reach between 230 GW and 450 GW in installed wind energy capacity by 2050 in order to meet decarbonization targets.

Germany led the expansion of wind energy in 2022 by adding 2.7 this year, GW; followed by France (2.1 GW) and the United Kingdom (1.7 GW). Of the new facilities, 87% were onshore energy, in the cases of Germany, Sweden and Finland. Almost half of the remaining offshore occurred in the United Kingdom. Throughout 2022, wind generation consolidated itself as one of the main sources of renewable energy (IBERDROLA, 2022).

Table 1 – Wind energy generation in the world

Continent	Median	Average	SD	Coef. of determination (R^2)	Equation	Value-p $^{(1)}$	Value-p
Africa	2.407,88	4.190,20^{D}	4.189,03	86,90%	y=757,77x - 2719,1	**<0,001**	**0,001**
Asia	98.490,21	208.512,74^{A}	255.426,46	80,06%	y=33697x - 195846	**<0,001**	
Central America and Caribbean	1.110,67	2.406,59^{D}	2.335,29	87,06%	y=321,27x - 1448,7	**<0,001**	
Eurasia	4.734,47	9.681,60^{C}	12.103,41	80,45%	y=1600,6x - 9525,5	**<0,001**	
Europe	182.761,36	219.018,66^{A}	162.858,75	96,02%	y=23529x - 63332	**<0,001**	
Middle East	222,12^{E}	815,89^{E}	1.419,81	49,20%	y=146,84x - 946,16	**<0,001**	
America of North	132.690,13	168.752,02^{A}	155.489,41	93,37%	y=22153x - 97082	**<0,001**	
Oceania	8.096,96	9.962,11^{B}	9.164,19	91,01%	y=1289x - 5506	**<0,001**	
South America	3.263,62	25.427,63^{C}	35.859,54	74,51%	y=4563,9x - 29339	**<0,001**	

Source: Adapted from IRENA (2024).
Legend: (1) Mann-Kendall Test; (2) Kruskal Wallis Test; (3) Averages followed by the same letter do not differ statistically from each other.
Note: The Bonferroni test was applied at a significance level of 5%.

North America, in turn, has the USA and Canada, which have developed through the generation of this energy matrix, in view of tax incentive programs, such as the Production Tax Credit (PTC) and the Investment Tax Credit (ITC). These boosted the development of wind projects, especially in states like Texas and California, where significant growth of wind farms has occurred in the provinces of Ontario and Quebec (DOE, 2022).

The northern region of America is showing significant growth in the wind energy market in recent decades. The Mordor Intelligence report (2025) projected in 2024 a growth of approximately 7.34% per year until 2027. The reduction of cost contributed to the increase in installed capacity in the region, where they were achieved 154,691 GW. With the United States, 132,696 GW were reached. Already with Canada, 12,304 GW were reached. In addition, government policies combined with investments in wind projects favored this scenario. The region has a strong commitment to energy onshore wind, although offshore is still incipient, especially in the United States.

The growth of this variable in Asia can be attributed to the strategic plans implemented in China, among them the Five-Year Plans, with subsidies and ambitious goals to reduce dependence on fossil fuels. In addition, there are government policies robust with subsidies and ambitious emission reduction targets. Tax incentives and investments in infrastructure also led to significant growth in India, as disclosed by the IEA (2021).

It is worth mentioning that the presence of wind energy is even stronger in Asia, since, according to IRENA, this continent can increase its installed onshore capacity, which was 230 GW in 2018, to more than 2600 GW by 2050. Therefore, it became a global leader in onshore wind energy, corresponding to 50% of all installed capacity and more than 60% of all installed offshore capacity in global terms (Godoi, 2019).

Another fact to be considered is that not only the financial capacity, but also the advanced technological contributions – reflected in investments in technology and innovation that result in cost reduction –, greater turbine efficiency, in addition to financial markets developed facilitated the financing of large wind infrastructure projects. This scenario makes these regions the largest generators of wind energy in the world.

In the sequence shown in Table 1, Oceania is observed. This region occupies statistically the second largest position in the world in wind energy generation. In this region, Australia was the main highlight, when it comes to the expansion of wind farms. Therefore, led this growth, which was driven by policies to encourage renewable energy renewables and abundance of wind resources. In New Zealand, the growth of generation of this energy occurred on a smaller scale, due to its traditional focus on hydroelectric energy, as attested by the Global Wind Energy Council (GWEC, 2024).

South America is included in the third group, followed by Central America and the Caribbean. In these regions, fossil fuels represent two-thirds of the energy matrix (a percentage lower than the global average of 80%), due to the 60% share of renewables, which helps to reduce dependence on these pollutants. In addition, hydroelectric power holds 45% of the supply, and electricity from countries like Paraguay and Costa Rica comes almost entirely from renewable sources.

However, fossil fuels are dominant in several sectors. Oil is the main means for transport, despite using biofuels in road transport in a proportion twice as high as the global average (IEA, 2023).

Finally, it should be noted that Latin America and the Caribbean hold vast natural resources and a diversified economy, which gives the region a privileged position to lead the global energy transition and thus make 80% of the energy generated renewable by 2050 (Garcia, 2023).

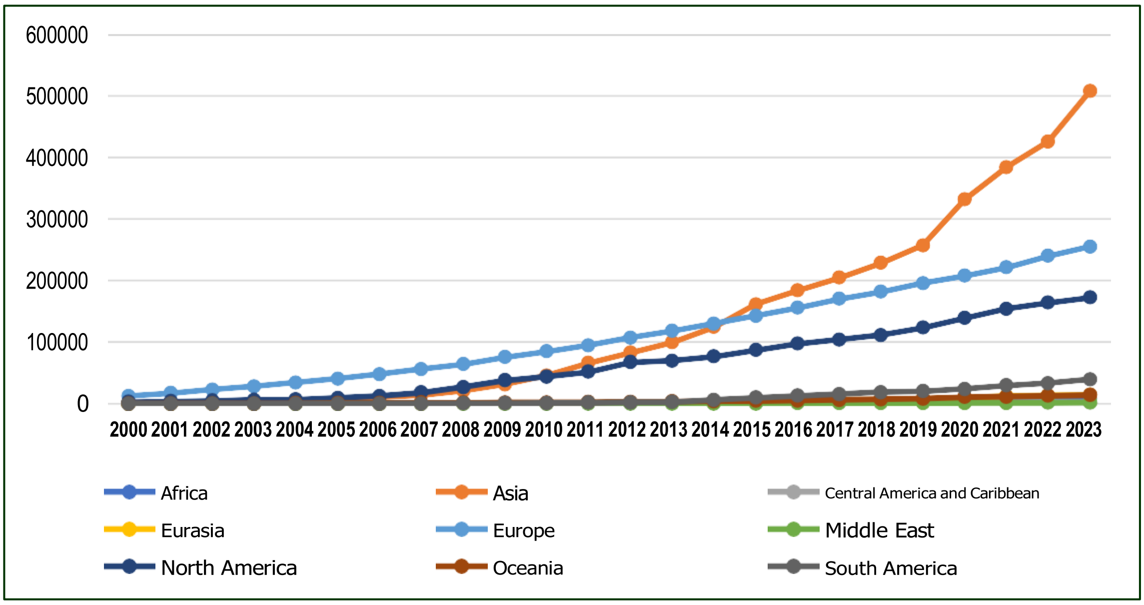
4.1.2 Installed energy capacity in the world

Considering the variable Installed capacity of wind energy generation, there is emphasis on the continents of Europe and North America. More markedly, Asia, which presented, between 2000 and 2023, significant growth, especially after 2014, when it supplanted Europe. In this sense, statistical results are presented in Table 2, a follow.

Attributing a significance level of 5%, using the Mann-Kendall test, there are statistical evidence of a positive trend, between the years 2000 and 2023, regarding the installed capacity in all continents. Furthermore, through the Kruskal-Wallis test, there is evidence of statistical difference in installed capacity between continents. In this case, Europe, Asia and North America presented greater electricity generation. These regions remained, statistically, in the group with the highest world average in capacity installed wind energy.

Regarding this scenario, it is worth highlighting the growth of installed capacity in Asia in 2018, which corresponded to 228,977.53 MW and even exceeded the installed capacity of generation in Europe this year, which was 181,787.40 MW (IRENA, 2024).

Figure 2 – Installed wind energy capacity in the world (MW)



Source: Adapted from IRENA (2024).

In Europe, wind technology increased its annual production in 2023 on the continent by 51.1%, which exceeded the maximum installed capacity in 2022, with a total of 19.1 GW of new installations. Germany led the expansion of wind energy in 2022 by adding 2.7 GW; followed by France (2.1 GW) and the United Kingdom (1.7 GW). Of the new installations, 87% were onshore energy (land). This is what happened in Germany, Sweden and Finland. By contrast, almost half of the remainder was offshore (sea). This scenario was observed in the United Kingdom, while France inaugurated its first. Throughout the year, wind generation consolidated itself as one of the main sources of renewable energy (Iberdrola, 2022).

In Asia, the presence of wind energy is even stronger. According to IRENA (2024), the continent can increase its installed onshore capacity from 230 GW, in 2018, to more than 2600 GW by 2050. In this way, the continent would become a global leader in onshore wind energy, corresponding to 50% of all installed capacity and more than 60% of all installed offshore capacity in global terms (Godoi, 2019).

China, in particular, has shown great prominence in the context of renewable energies. The country holds almost two-thirds of the world's utility-scale wind and solar energy in construction. According to the Global Energy Monitor (GEM), the six main provinces in wind installation (Mongolia, Xinjiang, Hebei, Shanxi, Shandong and Gansu) account for 43% of the country, although the distribution of onshore energy has remained stable, there has been a strong advance of offshore wind energy, starting with the province of Jiangsu (Prasad, 2024).

Table 2 – Installed wind energy capacity in the world

Continent	Median	Average	SD	Coef. of determination (R	Equation	Value-p	Value-p
Africa	1.063,49	2.617,94^{C}	2.804,39	86,22%	738127	**<0,001**	
Asia	74.429,29	133.613,81^{A}	152.053,05	84,24%	y=19736x-4E07	**<0,001**	
Central America and Caribbean	605,40	861,52^{C}	798,45	90,87%	y=107,64x-215652	**<0,001**	
Eurasia	2.009,64	3.987,28^{B}	4.704,09	83,96%	y=609,59x-1E+06	**<0,001**	
Europe	100.953,20	112.853,12^{A}	76.205,01	97,94%	y=10665x – 2E+07	**<0,001**	**<0,001**
Middle East	111,10	377,39^{D}	513,54	68,88%	y=60,275x - 120866	**<0,001**	
North America	59.565,83	66.431,63^{A}	56.161,44	95,82%	y=774,5x - 2E+07	**<0,001**	
Oceania	3.018,04	4.488,04^{B}	4.314,89	88,63%	y=574,47x - 1E+06	**<0,001**	
South America	1.998,63	9.260,35^{B}	12.326,34	77,85%	y=1538,1x - 3E+06	**<0,001**	

Source: Adapted from IRENA (2024).

Legend: (1) Mann-Kendall test; (2) Kruskal Wallis test; (3) Averages followed by the same letter do not differ statistically from each other.

Note: The Bonferroni test was applied at a significance level of 5%.

The high growth of China, which occurred between 2014 and 2015, as well as the anticipation of reductions in the onshore wind feed-in tariff (FIT) drove a race to install and connect projects. Official statistics reported that wind capacity connected to the grid reached 96.37 GW at the end of 2014, with approximately 19.81 GW newly commissioned.

According to the China Wind Energy Association, total wind installations, in that year, reached 114.76 GW. Of these, 23.35 GW were new (Yang, 2015). The approval of these measures in China, therefore, effectively contributed to Asia surpassing the installed capacity of the European continent in the following years. This indicates the significant efforts of China, with regard to reducing energy dependence on coal and oil.

In view of this context, it is worth noting that, despite the statistical average of Installed Wind Capacity in the European and American regions, each of them used different instruments to reach this level of installed capacity. The European Union prioritizes non-fiscal incentives, such as carbon pricing, binding targets, standards of performance, sector regulation, direct technology mandates, subsidies and support financial, in addition to financial tax incentives, such as tax credits and loans. (European Parliament, 2025). The USA uses financial tax incentives, such as tax credits and loans (EDP Renewables, 2025).

The northern region of America is showing significant growth in the wind energy market in recent decades. The Mordor Intelligence report projected in 2024 a growth of approximately 7.34% per year until 2027. The cost reduction encouraged the increase in installed capacity in the region, which reached 154,691 GW with the United States, 132,696 GW, followed by Canada with 12,304 GW, in addition, policies governmental policies allied with investments in wind projects favored this scenario. The region has a strong commitment to onshore wind energy, although offshore is still incipient, especially in the United States (Mordor Intelligence, 2025).

The U.S. has had part of its international policy directed by oil interests and by guaranteeing its own energy security for much longer than China. This is basically due to two reasons:

(I) the protection of the interests and investments of North American oil companies installed abroad began in the early twentieth century, when these began to operate beyond their borders, but intensified from 1947, when the U.S. began to import oil;

(II) (II) from 1970, the country reached its maximum production capacity and passed to be really dependent on imports.

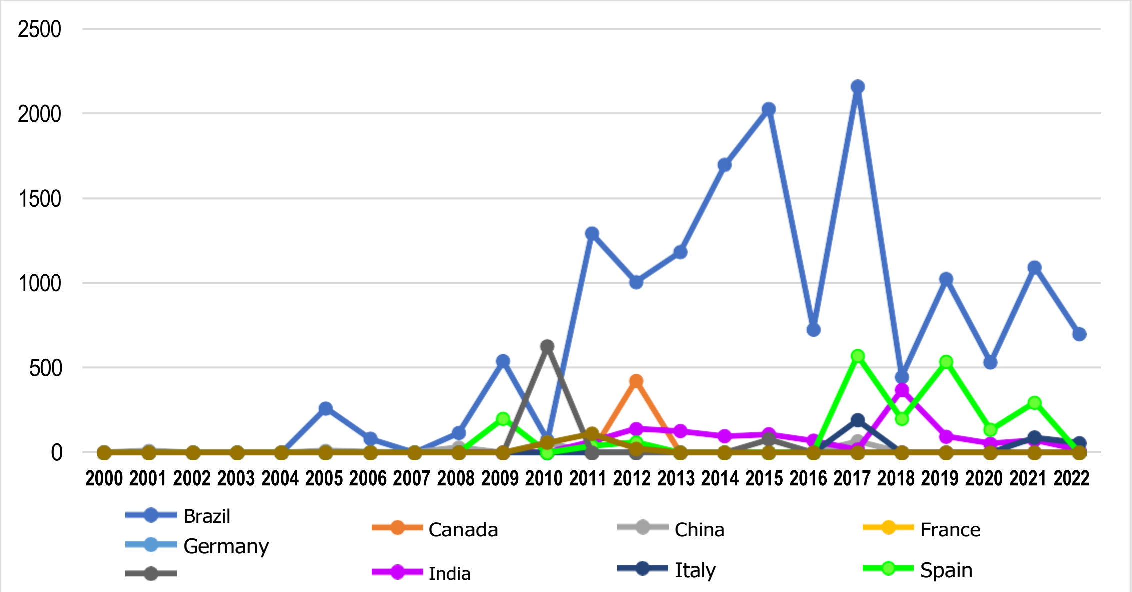
All the ramifications of this growth, on their respective continents, contributed to the quite expressive result of the installed capacity of this energy matrix. In the context worldwide, wind generation reached 906 GW of installed capacity. 92.9% of this total corresponded to the participation of onshore parks, which is equivalent to 842 GW. The participation offshore corresponded to 7.1%, which is equivalent to 64 GW. In the decade from 2013 to 2022, the capacity installed of wind generation evolved to the average rate of 12.3% p.a. in the world (GWE, 2023).

4.1.3 Public investments (in $) in onshore wind energy – ten largest

As presented in Graph 3, the behavior of the public investment variable in onshore energy presented significant differences, which were evidenced in the application of the applied statistical tests, according to the results recorded in Table 3, below.

With regard to onshore energy, the beginning of the investment, in Brazil, in this matrix energy, occurred only from 2004. However, this occurred in a little substantial, given the growth observed statistically, from 2010. O Graph 3 demonstrates a peak of growth in 2014, with regard to the period in which the participation of renewable energies in the Brazilian energy matrix remained among the most among the highest in the world, according to the EPE (2015) report, with 40.4% (Brazil, 2013) compared to 13.2% (World, 2012).

Figure 3 – Public investments (in $) in onshore wind energy – ten largest countries



Source: Adapted from IRENA (2024).

Assigning a significance level of 5%, using the Mann-Kendall Test, there are statistical evidence of a trend, between the years 2000 and 2022, regarding investments public (in $) in onshore wind energy in Brazil, India, Italy and Spain. Furthermore, through the Kruskal-Wallis Test, there is evidence of a statistical difference in public investments in onshore wind energy between the countries under analysis. Brazil presented the largest public investment in the area of onshore wind energy.

Investments in electricity production from wind sources reached 12,210 GWh in 2014, equivalent to an increase of 85.6% compared to the previous year, when it reached 6,578 GWh (EPE, 2015). In 2011, Brazil was already recognized for its conditions favorable natural conditions, mainly for the generation of onshore wind energy. The combination of constant and good speed winds, especially in regions such as the Northeast, provided an ideal environment for the installation of wind farms, which boosted investments in the sector (GWEC, 2011).

Also in 2011, the improvement of equipment and the specialization of labor allowed the reduction of costs and the increase in the competitiveness of onshore wind projects , making investments even more attractive and providing technological advancement. With this, it is possible to consolidate an efficient local production chain (ABEEólica, 2011).

Table 3 – Public investments (in $) in onshore wind energy – ten largest countries

Country	Median	Average	Deviation Standard	Coef. Of determination (R	Equation	Value-p	Value-p
Brazil	531,51	$650,46^{A}$	678,62	40,45%	y= 63.636x - 113.17	**<0,001**	**<0,001**
Canada	0,00	$18,48^{C}$	88,62	0,10%	Y= 0.42x + 13.439	**0,940**	
China	0,10	$8,32^{D}$	18,72	0,00%	Y= 0.0016x + 8.3043	**0,580**	
France	0,00	$0,00^{E}$	0,00	---	---	---	
Germany	0,00	$0,00^{E}$	0,00	---	---	---	
India	16,35	$54,00^{B}$	83,93	25,76%	Y= 6.2812x - 21.375	**<0,001**	
Italy	0,00	$14,65^{C}$	44,05	16,41%	Y= 2.6306 x - 16.92	**<0,023**	
Spain	0,00	$88,68^{B}$	168,47	26,49%	Y= 12.785x - 64.736	**<0,010**	
United Kingdom	0,00	$30,62^{C}$	130,86	0,03%	Y= - 0.3106x + 34.347	**0,828**	
USA	0,00	$8,45^{D}$	25,95	0,00%	Y= - 0.0344x + 8.8641	**1,000**	

Source: Adapted from IRENA (2024).

Legend: (1) Mann-Kendall test; (2) Kruskal Wallis test; (3) Averages followed by the same letter do not differ statistically from each other.

Note: The Bonferroni test was applied at a significance level of 5%.

It is also worth highlighting measures such as auctions and support programs for clean energy, which offered legal and financial security to investors. This scenario contributed to Brazil standing out in the global onshore energy scenario. This occurred as a result of measures such as those mentioned throughout this study, aimed at diversification of the energy matrix and the incentive to renewable sources, which were fundamental to attract investments (EPE, 2011)

In addition, a relevant business environment was formed in this period, given the improvement of specific standards for renewable energy, as well as the stability of the Brazilian regulatory framework. These were decisive factors in attracting both investors national and foreign, who found in the country a reliable scenario to develop wind energy projects (MME 2011).

In this sense, offshore systems are evolving, given the promising growth of this alternative for transmission, security, supply and energy sustainability, including in terms of cost. Acaroglu and Marquez (2022) verified the economic viability of offshore wind installations dividing this process into three parts, namely: construction of undersea infrastructures; (2) installation of towers, nacelles and rotor blades; and (3) connection of power grid. The finding of this study, carried out through sensitivity analysis, was that that the best solutions and incentives for economic and environmental advantages were the government subsidies for infrastructure and environmental costs. This work emphasizes the continuous reduction of installation costs for offshore wind farms.

Between 2010 and 2023, the wind energy sector in Brazil received almost 50 billion dollars in investments, generating more than 68,000 direct jobs. Furthermore, it is worth highlighting that, in the third quarter of 2023, CCEE (Electric Energy Commercialization Chamber) pointed out Piauí as the state with the highest growth in wind energy generation in 2022, registering an increase of 24.85% compared to 2021, as described by Lages (2024).

From a statistical perspective, on average, India and Spain were in the second block of investors in onshore energy. In India, the government implemented a series of policies incentives, such as competitive auctions, targets for renewable energy production, and tax benefits that stimulated large investments in onshore energy. In Spain, in the 2000s, pioneering policies were associated with feed-in tariffs in tariffs) and support mechanisms (IEA, 2018). These government incentives and policies support created an environment conducive to the sustainable growth of the sector.

Furthermore, it is relevant to highlight that India has vast areas with significant wind potential, significant, especially in states like Tamil Nadu and Gujarat, which favored the installation of large-scale onshore wind farms. In turn, Spain has regions of high wind speeds, such as the Meseta Central and coastal areas. Its conditions natural transformed the region into one of the leaders in wind energy in Europe (GWEC, 2020).

Also relevant factors are the commitment to reducing greenhouse gas emissions greenhouse gases and the need to diversify energy matrices, which were determinants for both countries.

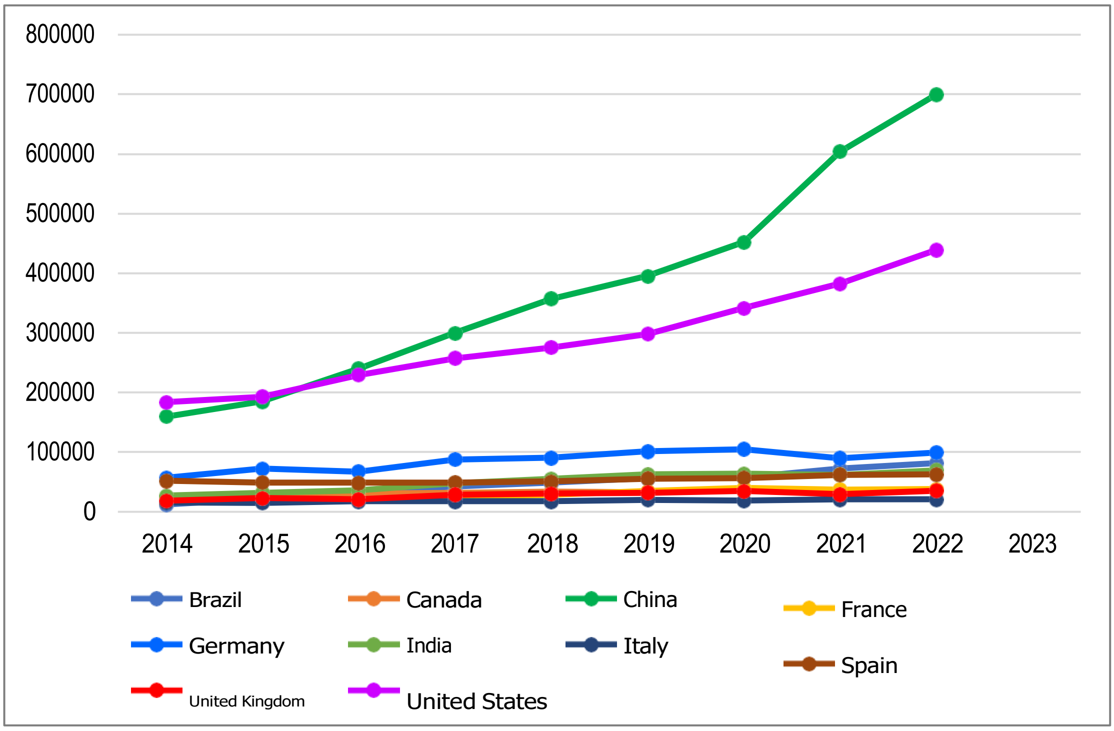
India, although facing challenges related to energy security and pollution, and Spain, driven by the European Union's guidelines for energy transition, channeled investments into the sector onshore as part of their sustainable development strategies (MNRE, 2020; Miteco, 2021).

In both countries, investments in technological innovation and the consolidation of chains local production allowed the reduction of installation and operation costs. India expanded its industrial base for the production of turbines and components, while Spain already benefited from a consolidated know-how in the sector of specialized companies, which further boosted investments (BNEF, 2021).

4.1.4 Onshore wind energy by country – ten largest

Through the collection of data and the analysis of onshore energy generation referring to the ten largest countries in the world, the following results were obtained.

Graph 4 – Onshore wind energy generation – ten largest countries (GWh)



Source: Adapted from IRENA (2024).

Assigning a significance level of 5%, using the Mann-Kendall Test, there are statistical evidence of a trend, between the years 2014 and 2023, regarding the generation of electricity (GWh) in onshore wind energy in Brazil, Canada, China and India. Furthermore in addition, through the Kruskal-Wallis test, there is evidence of a statistical difference in the generation of electricity (GWh) in onshore wind energy between countries. In this case, China, Germany and The United States had the highest electricity generation (GWh) in onshore wind energy.

The behavior shown in Graph 4 corroborates the results achieved in the application of the statistical tests described in Table 4. With regard to energy generation onshore, statistically, on average, China and Germany do not differ significantly. Furthermore, a survey carried out with the ANEEL Generation Information System (SIGA) recorded, in March 2023, a total of 904 onshore wind farms in operation with installed capacity.

With regard to onshore energy generation, statistically, on average, the countries of China, Germany and the United States do not differ significantly. Firstly, in relation to China, one of the factors that contributed to its leadership in the onshore wind sector were the investments and technological advances, which resulted in a decrease in production costs and installation. Specifically, between 2010 and 2022, the average costs of wind projects decreased by about 69% (Mendonça; Nunes; Ungaretti, 2024).

Table 4 – Onshore wind energy generation – ten largest countries (GWh)

Continent	Median	Average	SD	Coef. of determi-nation(R	Equation	Value-p	Value-p
Brazil	45.424,20	42.512,71^{B}	26.009,49	15,37%	y=3367.7 + 23990	**<0,020**	
Canada	32.192,00	28.690,40^{B}	10.991,93	2,57%	y=-582.33 + 31893	**0,032**	
China	328.589,10	339.275,19^{A}	210.504,29	15,26%	y=27161x + 189887	**<0,020**	
France	26.604,02	26.322,41^{B}	12.212,53	1,88%	y=553.3x + 23279	**0,074**	
Germany	88.906,50	77.095,10^{A}	31.224,46	0,78%	y=-909.36 + 82097	**0,210**	<0,001
India	51.339,22	45.597,70^{B}	21.715,59	2,94%	y=1230.6 + 38830	**<0,049**	
Italy	17.729,17	16.355,43^{B}	6.104,09	5,13%	y=-456.45 +18866	**0,107**	
Spain	51.443,50	48.710,30^{B}	17.864,10	8,35%	y=-1705x + 58088	**0,210**	
United Kingdom	28.939,40	25.221,71^{B}	10.513,10	0,11%	y=-114.51 + 25852	**0,107**	
USA	266.438,83	260.069,49^{A}	122.171,08	2,78%	y=6729.4x + 223058	**0,020**	

Source: Source: Adapted from IRENA (2024).

Legend: (1) Mann-Kendall test; (2) Kruskal Wallis test; (3) Averages followed by the same letter do not differ statistically from each other.

Note: The Bonferroni test was applied at a significance level of 5%.

It is also possible to highlight government economic incentives in order to promote wind energy. Although these subsidies suffered a considerable drop in 2022, the sector managed to overcome itself in the following year and returned to its growth, reaching double its development in the 12 annual months (Prasad, 2024).

In the last 10 years, the annual increase in wind capacity in the USA was on average 9%, slightly exceeding that of Europe. In that same period, however, despite the continuous continuous, the country remained below the global average growth rate, which was 13% per year, as reported by Ember (Maguire, 2024).

Also on the USA, it is possible to list technological advances as a factor that contributed to the development of wind energy in the country. In 2024, the sector was responsible for a record share in energy production and became the second largest source of clean energy in the American system. In addition, there has been a recent drop in the costs of development and tax profits, which makes it possible to project growth in 2025 (Maguire, 2024).

In Germany, technological advances were also relevant. Wind turbines have become larger and more modern, new materials and designs have improved performance of systems, in addition to digitization. This improves the control and maintenance of turbines and reduces operating costs. However, the country faces regulatory challenges regarding approval of new projects, which are resistant to its expansion (Wolfenstein, 2023).

Also listed is the Law to encourage renewable energies, which came into force in the year of 2015, the EEG 2.0 (Erneuerbare Energien Gesetz – Renewable Energy Sources Act). This reflected the adjustment in the country's energy policy, accompanied by the declaration of abandonment of nuclear energy in favor of the energy transition. This change in positioning occurred due to pressure from the industrial and electrical sector, in addition to the European Union itself (Época Negócios, 2015).

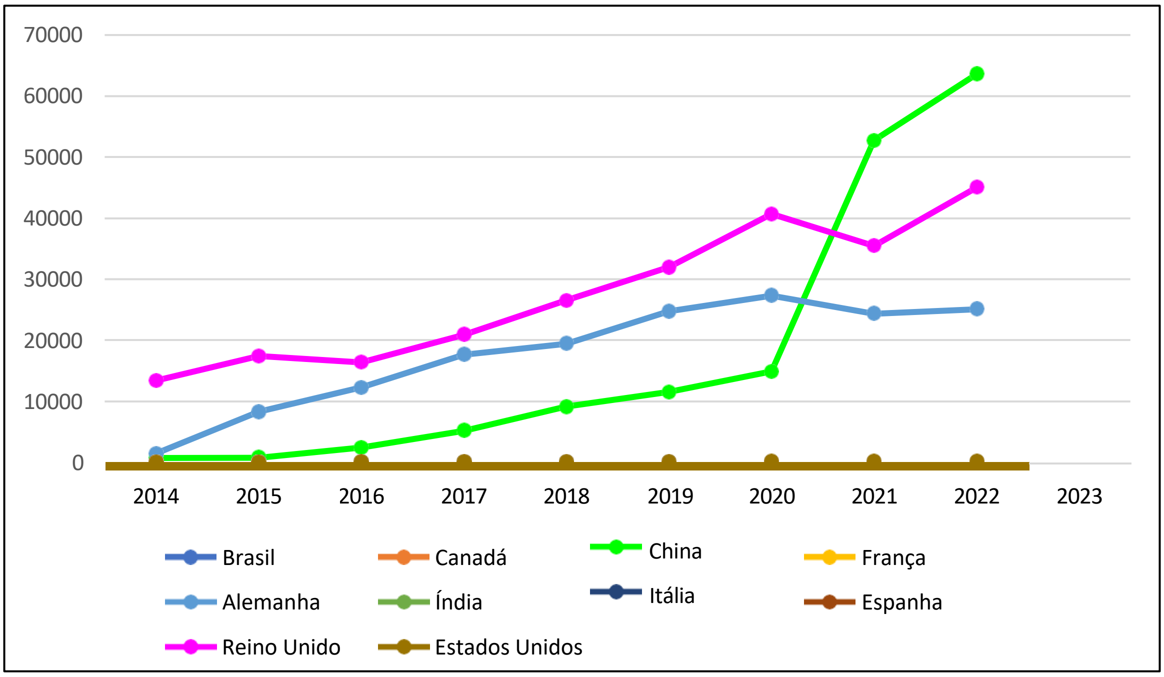
4.1.5 Offshore wind energy generation by country

Attributing a significance level of 5%, using the Mann-Kendall test, there are statistical evidence of a trend, between the years 2000 and 2023, regarding the generation of electricity (GWh) in offshore wind energy in China and the United Kingdom. Furthermore, through the Kruskal-Wallis test, evidence of a statistical difference in the generation of electricity (GWh) in offshore wind energy between countries was obtained. The United Kingdom presented greater electricity generation (GWh) in offshore wind energy.

With regard to the first block, defined with an index (letter) in each value of the third column, made up of countries that do not differ, on average, statistically, is the United Kingdom. This is the country that stood out in offshore energy generation between the years 2014 and 2023. The expansion was influenced by several factors.

As the first of these, it is possible to list government policies and energy targets. The country became the first major economy to halve its emissions of dioxide of carbon, the main industrial pollutant, between 1990 and 2022. At the same time, it increased its economy by 79%, according to data from the local government (Brito, 2024). The government also has set a target to further expand the offshore wind sector, which is already very well established. One of these goals is to reach 50 GW of capacity by 2030 (Andrade, 2023).

Gráfico 5 – Geração de energia eólica offshore – dez maiores países (GWh)



Fonte: Adaptado de IRENA (2024).

Vale ressaltar que o governo britânico reconheceu a insuficiência da fonte eólica *onshore* de suprir as demandas da política energética sustentável. Além disso, a *offshore*, a maremotriz e a energia das ondas seriam insubstituíveis para alcançar tais metas de grande escala. Outro fator que contribuiu para que atualmente o país se tornasse o maior mercado de energia eólica *offshore* do mundo diz respeito às rodadas de licitações e incentivos, os conhecidos "Contratos por Diferença" (CFD). Trata-se de contratos de longo prazo, por meio dos quais se paga ao gerador de energia renovável a diferença entre preço de mercado da eletricidade e um preço de longo prazo. Dessa forma, há incentivo governamental direcionado a energias renováveis por meio de leilões de contrato de geração de energia limpa (Paiva, 2021).

Cabe mencionar também os avanços tecnológicos em relação às turbinas britânicas. As turbinas do Reino Unido geraram 24 terawatts-hora (TWh) de eletricidade entre janeiro e março, o que foi capaz de atender a 11,5 milhões de residências. Um dos seus principais parques, Hornsea 2, possui uma instalação de 165 turbinas com capacidade de produção de mais de 1,3 GW (Andrade, 2023). Além disso, de acordo com notícia publicada pela CNN Brasil (2023), o país protagoniza atualmente a instalação do maior parque eólico do mundo, o Dogger Bank, que conta com 277 turbinas. A previsão de conclusão da obra é o ano de 2026.

A redução de custos, uma consequência da economia de escala, tornou a indústria madura e eficiente, precedida de avanços tecnológicos e inovações. Ademais, houve maior competitividade no mercado fornecedor (sobretudo, chinês). Isso contribuiu para a ampliação of the turbine offer, the support structure, installation services and collaboration expected from stakeholders. In addition, better planning is carried out in relation to the park wind power and mass production of components, increasing productivity. These are other variables that influence offshore wind energy costs (Santioso et al., 2023).

Table 5 – Offshore wind energy generation (GWh) – ten largest countries

Countries	Median	Average	SD	Coef. of determination nation (R	Equation	Value-p	Value-p
Brazil	0,00	0,00^{E}	0,00	---	---	**1,000**	
Canada	0,00	0,00^{E}	0,00	---	---	**1,000**	
China	7.144,75	16.091,93^{B}	22.856,11	33,03%	y = 4338,9x - 7772,1	**<0,020**	
France	0,00	0,00^{E}	0,00	---	---	**1,000**	
Germany	18.571,00	16.071,90^{B}	10.071,63	13,19%	y = 1207,9x + 9428,2	**0,074**	**<0,001**
India	0,00	0,00^{E}	0,00	---	---	**1,000**	
Italy	0,00	0,00^{E}	0,00	---	---	**1,000**	
Spain	11,00	9,90^{D}	3,48	27,27%	y = - 0,6x + 13,2	**0,164**	
United Kingdom	23.720,56	24.785,98^{A}	13.804,48	9,58%	y= 1410,9x + 17026	**0,049**	
USA	102,67	84,51^{C}	61,08	16,38%	y= 8,1653x + 39,603	**0,109**	

Source: Adapted from IRENA (2024).
Legend: (1) Mann-Kendall test; (2) Kruskal Wallis test; (3) Averages followed by the same letter do not differ statistically from each other.
Note: The Bonferroni test was applied at a significance level of 5%.

Finally, public acceptance and socioeconomic impacts contributed to the advancement of the sector in the United Kingdom. Its growth helped generate direct and indirect jobs. Furthermore, studies indicate that the presence of turbines did not significantly devalue coastal properties, due to preventive measures, such as distancing from the coast. This made that public acceptance of these parks remained high (Agências, 2024).

The second group of countries with offshore wind energy generation, with averages statistically identical, is made up of China and Germany. Among the factors that influenced the growth of this variable in China are capacity targets, advances technological, investments, regulatory and market challenges, in addition to policies governmental.

Technological advances have driven the Chinese offshore wind market with the objective of maximizing the use of wind energy. Thus, the manufacturers of equipment is in the process of building larger wind turbines, capable of supporting strong winds, such as typhoons and hurricanes. Ocean X reflects this goal and stands out as the first offshore double-headed wind turbine with a rated power of more than 16MW (Méndez, 2024).

With regard to regulatory and market challenges, despite the considerable growth, China has faced barriers related to its regulatory structure and international competitiveness. Offshore projects in the country were complex due to the set of national and local rules. Faced with this, there was a regulatory simplification in order to attract foreign and local investors and mitigate such challenges (EPE, 2024).

As for global competitiveness, the country suffers from the reduction in prices of turbines wind power, since, although it is more accessible, it still interferes with the financial sustainability of manufacturers. Furthermore, trade conflicts, especially with the United States, harm the expansion of Chinese companies in Western markets, which leads to the search for markets emerging markets, such as Saudi Arabia and other countries with budgetary restrictions and prices competitive (Financial Times, 2024).

The Chinese government has also implemented several policies and incentives that boosted offshore power generation. The "National Medium and Long-Term Program for the Development of Science and Technology (2006-2020)", launched in 2006, stood out by emphasizing the importance of technological innovation and establishing clear goals for advancement in strategic sectors, including renewable energy. Furthermore, it was configured as incentive and provision of public funding for priority projects, which included the acquisition of natural resources, exploration of technological capabilities and development of infrastructure that encourages exports. Such investments were fundamental to the international expansion of Chinese companies in the energy sector.

Furthermore, initiatives such as "Program 863" (launched in 1986) and "Program 973" (launched in 1998) were Research and Development (R&D) Programs implemented by China. These initiatives focused on technological advancement in key areas, including the electronics and renewable energy industries. They also aimed to strengthen the capacity of domestic innovation and reduce dependence on foreign technologies. This scenario demonstrates the Chinese government's commitment to promoting sustainable development and technological, positioning the country as a global leader in offshore power generation.

Still in relation to the second block, in which Germany is included, can be listed the policies and incentives adopted by the country to boost the offshore power generation. Among them are the Feed-in Tariff system, implemented in

1991, which guaranteed fixed and long-term tariffs for renewable energy producers, including offshore wind, in addition to providing security to investors and stimulating the expansion of the sector.

The legislation that replaced the previous system is also among these initiatives, which reinforces support for renewable energies with differentiated tariffs by technology and contracts of long term. It also guaranteed priority access to the electricity grid for offshore generated energy, called the Renewable Energy Sources Act (EEG) of 2000. This law centralized the planning and bidding of maritime areas suitable for offshore projects, facilitating the orderly development of the sector, and established ambitious targets for installed capacity of offshore wind energy: 30 GW by 2030, 40 GW by 2035 and 70 GW by 2045. This is the Offshore Wind Energy Act (WindSeeG) of 2016. Finally, it considered the introduction of subsidies, tax incentives and loans with favorable conditions for energy projects renewable, including offshore.

With this, the aim was to reduce initial costs and make investments more attractive, in the year 1991, in addition to the implementation, since 1974, of public policies for research and development for renewable energies. These policies and incentives demonstrate the Germany's continued commitment to promoting offshore wind energy, positioning the country as one of the world leaders in this sector.

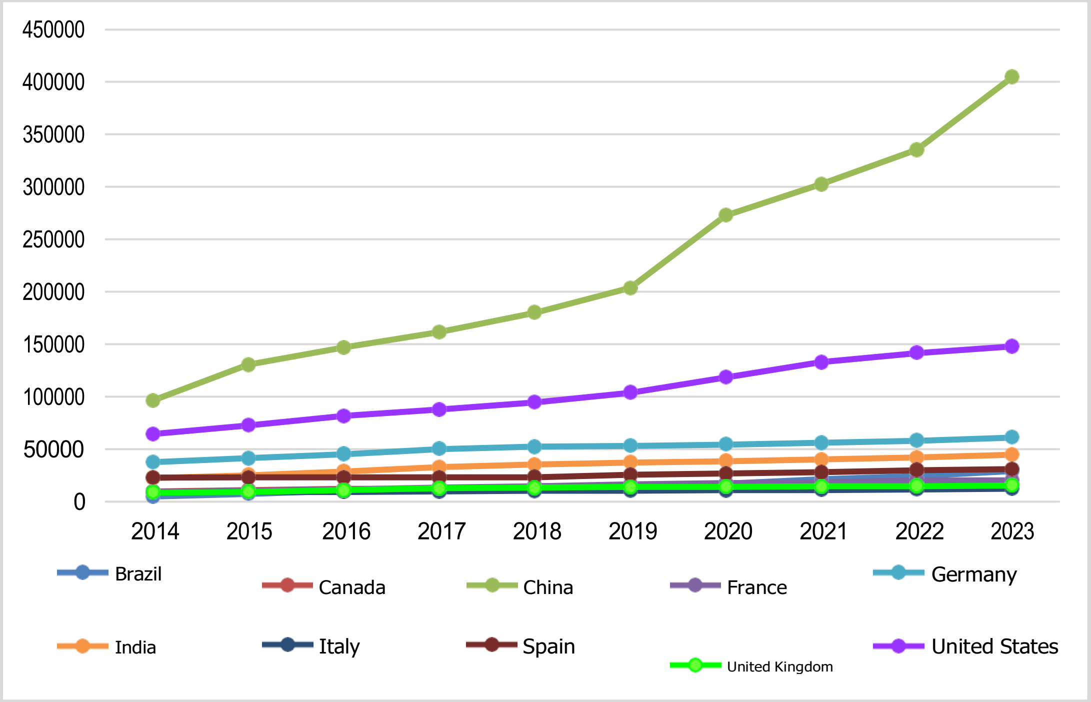
4.1.6 Installed onshore wind energy capacity

Attributing a significance level of 5%, using the Mann-Kendall test, there are statistical evidence of a trend, between the years 2014 and 2023, regarding the capacity installed onshore wind energy (MW) in all countries analyzed.

Furthermore, using the Kruskal-Wallis test, it is observed that there is evidence of statistical difference in installed capacity (MW) in onshore energy between countries. China, Germany and the United States presented greater installed electricity capacity (MW) in onshore energy.

Corroborating this finding, a description carried out by the WEO (2024) points out that several countries are adopting measures to strengthen domestic clean energy manufacturing. According to the same report, the US and the EU offer large incentives through laws specific, while about 10% of the US$2 trillion invested globally since 2020 require local content. In addition, some governments are implementing tariff adjustments and antidumping measures to address challenges in the trade of clean energy technologies.

Figure 6 – Installed capacity of onshore wind energy (MW)



Source: Adapted from IRENA (2024).

Antidumping measures represent actions taken by governments to protect the domestic industry against the practice of dumping, which occurs when foreign companies sell products in the domestic market at artificially low prices, often lower than the cost of production, in order to eliminate local competitors.

In Germany, the United States, and China, these measures are applied in the clean energy technology sector to prevent foreign manufacturers, especially from China, from selling components at prices considered unfair. These measures include additional tariffs on imported products, investigations to prove unfair practices, and imposition of quotas or trade restrictions, with the aim of ensuring more balanced conditions for local producers and encouraging the development of the domestic clean energy industry. (PV Tech, 2025; Associated Press, 2024)

These countries are part of the context of an increasingly global energy economy more electrified. Since 2010, this demand has increased by an average of 2.7% per year, while overall energy demand increased by 1.4% per year. Electricity is being used more and more by China, the USA and Germany, instead of fossil fuels, in order to provide heat, mobility and industrial energy demand. Innovations such as smart grids and advances in engine efficiency have also increased the appeal of electricity (WEO, 2024).

Table 6 – Installed capacity of onshore wind power (MW)

Continent	Median	Average	SD	Coef. of determination (R ^{2})	Equ tion	Value-p	Value-p
Brazil	15.140,73^{C}	15.689,39	7.524,32	97,25%	y=24,50,7 - 2210,3	**<0,001**	
Canada	13.018,00^{C}	13.049,14	2.023,34	91,93%	y=640,74 x + 9525	**<0,001**	
China	191.864,40^{A}	223.491,53	100.453,89	95,31%	y=32392x + 45335	**<0,001**	
France	15.649,95^{C}	15.249,95	4.037,89	98,82%	y=1325,8 x + 7958	**<0,001**	
Germany	52.757,50^{A}	50.929,30	7.444,24	94,55%	y=2390,9 + 37780	**<0,001**	**<0,001**
India	36.396,64^{B}	34.718,76	7.351,50	96,96%	y=2391x + 21568	**<0,001**	
Italy	10.454,86^{C}	10.410,27	1.189,22	99,37%	y=391,55x + 8256,8	**<0,001**	
Spain	24.492,57^{B}	25.679,40	3.136,29	88,68%	y=975,51 + 20314	**<0,001**	
United Kingdom	13.711,99^{C}	12.741,13	2.396,29	89,92%	y=750,52x + 8613,2	**<0,001**	
USA	99.221,58^{A}	104.613,85	29.437,81	98,62%	y=9655,7 + 51508	**<0,001**	

Source: Adapted from IRENA (2024).

Legend: (1) Mann-Kendall test; (2) Kruskal Wallis test; (3) Averages followed by the same letter do not differ statistically from each other.

Note: The Bonferroni test was applied at a significance level of 5%.

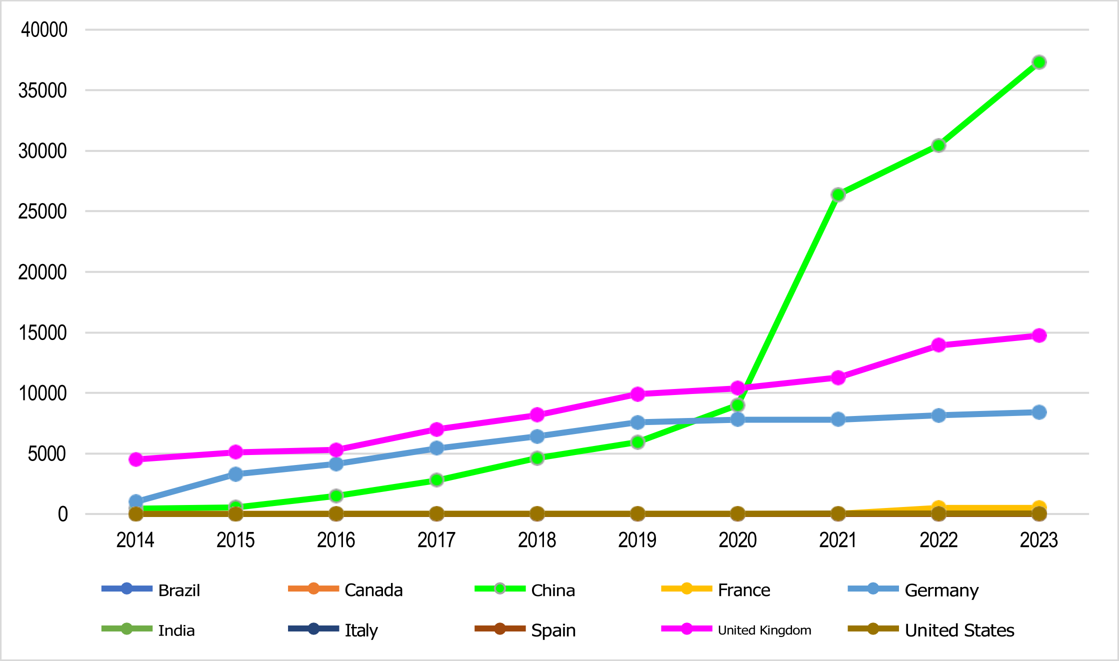
Finally, it is worth mentioning that, despite the generation of wind energy in Brazil having been started in 1992, with the Fernando de Noronha park, whose initial capacity was 75 KW, only in 2014 did a record occur, when the country exceeded the mark of 5 GW of installed wind power. This fact was driven by auctions promoted by the government, which contracted around 7.1 GW in new projects, carried out in 2011 and 2012, which began to impact the parks completed in 2014. This growth consolidated Brazil as one of the main emerging wind markets in the world, which is why the participation of this country is observed, as presented in Graph 7.

4.1.7 Installed capacity of offshore wind power

As described by IBP (2023), offshore wind farms generate business opportunities, environmental and energy benefits, attracting investments, creating jobs and increasing government revenue, a scenario of high complexity due to the search for a balance between three pillars: energy security, access to energy at reasonable costs and decarbonization. The accelerated development of this source, as presented in Graph 7, started in 2020.

To reinforce the behavior presented in Graph 7, assigning a significance level of 5%, using the Mann-Kendall test, it is highlighted that there is statistical evidence of a trend between the years 2014 and 2023 regarding the installed capacity of offshore wind energy (MW) in China, France, Germany, the United Kingdom, and the USA. Furthermore, through the application of the Kruskal-Wallis test, evidence of statistical difference in installed electricity capacity (MW) in offshore wind energy between countries can be observed. In this case, China, Germany, and the United States showed greater capacity installed electricity (MW) in offshore wind energy.

Graph 7 – Installed offshore wind energy capacity (MW)



Source: Adapted from IRENA (2024).

In the context of European, Asian, and American countries, the rapid increase in low-emission electricity sources is a central part of the transition programs to clean energy. Many actions are underway to triple the global installed capacity of renewable energy by 2030. These actions were defined at the 28th Conference of the Parties of the Convention Framework of the United Nations on Climate Change (COP28), with the aim of, through a collective effort, reducing the growth of emissions that, over the years, have only slowed down since the beginning of the pandemic in 2019.

Regarding China, it is observed that it has demonstrated remarkable growth in installed offshore wind energy capacity between 2014 and 2023. In 2014, the capacity installed was approximately 565 megawatts (MW). This number increased to about

900 MW in 2015. In 2016, there was a significant increase of 592 MW, raising the total capacity to approximately 1.9 gigawatts (GW). Growth continued in the years subsequently, reaching 6.8 GW in 2019 and 9.9 GW in 2020. In 2021, this country added an impressive 16.9 GW, resulting in a total capacity of 26.38 GW. In 2022, the capacity increased to 31.5 GW, and estimates for 2023 indicate a capacity installed capacity of 54.7 GW. In 2023, the total capacity reached 37.7 gigawatts (GW), representing 50% of the global offshore wind energy capacity. (Statista, 2024)

The description of the statistical results that corroborate this scenario is described in Table 7, below.

Table 7 – Installed offshore wind energy capacity (MW)

Country	Median	Average	SD	Coef. of determination (R)	Equation	Value -p	Value -p
Brazil	0,00	0,00^{C}	0,00	---	---	**1,000**	**<0,001**
Canada	0,00	0,00^{C}	0,00	---	---	**1,000**	
China	5.259,00	11.891,50^{A}	13.937,22	81,44%	y= 4154.3x - 10957	**<0,001**	
France	13,55	110,05^{B}	205,95	49,16%	y= 47.694x - 152,27	**<0,001**	
Germany	6.974,00	5.991,30^{A}	2.488,34	88,34%	y= 772.48x + 1742,7	**<0,001**	
India	0,00	0,00^{C}	0,00	---	---	**1,000**	
Italy	0,00	0,00^{C}	0,00	---	---	**1,000**	
Spain	5,00	5,20^{B}	0,63	27,27%	y= 0.1091x + 4,6	**0,164**	
United	9.034,30	9.024,20^{A}	3.634,58	97,54%	y= 1185.6x + 2503,2	**<0,001**	
USA	29,30	27,04^{B}	15,26	75,06%	y= 4.3665x + 3,028	**<0,003**	

Source: Adapted from IRENA (2024).

Legend: (1) Mann-Kendall Test; (2) Kruskal Wallis Test; (3) Averages followed by the same letter do not differ statistically from each other.

Note: The Bonferroni test was applied at a significance level of 5%.

The increase in installed capacity also suggests a strategic commitment by China to diversify its energy matrix and reduce carbon emissions, aligning with global environmental goals and contributing significantly to the global energy transition.

The United Kingdom, which has, on average, statistically the same capacity installed offshore wind energy as China, has consolidated itself as a world leader in installed offshore wind energy capacity. This was thanks to a combination of government subsidies and developed regulations. The UK government declared in 2019 that it will quadruple its offshore wind capacity to 40 gigawatts (GW) by 2030 as part of its attempts to achieve net-zero carbon emissions by 2050. This goal marks a considerable growth in the sector and demonstrates the government's acceptance of offshore wind power as a critical component of clean energy transition. (Gov. UK, 2023; Gov. UK, 2019)

Among the government subsidies developed by this country, the following stand out Contracts for Difference (CFD), whose mechanism guarantees a minimum price for electricity generated by renewable sources, providing financial security to investors. In 2023, the British government allocated £1.1 billion to offshore wind energy projects in the sixth CFD allocation round (ESGNEWS, 2024).

Another important subsidy was the provision of additional financial support that the government granted, of an additional £227 million to stimulate new ventures, recognizing the economic challenges faced by the sector, especially due to increased costs, due to the global increase in inflation and the impact on supply chains (Economia, 2023).

As favorable regulation, the country implemented a simplification of processes licensing with more agile consent procedures for offshore wind projects offshore, reducing bureaucracy and accelerating the development of new parks. There was also aid directed at facilitating access to strategic locations for the installation of turbines during the licensing of areas for offshore parks, carried out by the person responsible for the British seabed, the Crown Estate. . (Gov. UK, 2023; Gov. UK, 2019)

4.1.8 Installed energy capacity by region of Brazil

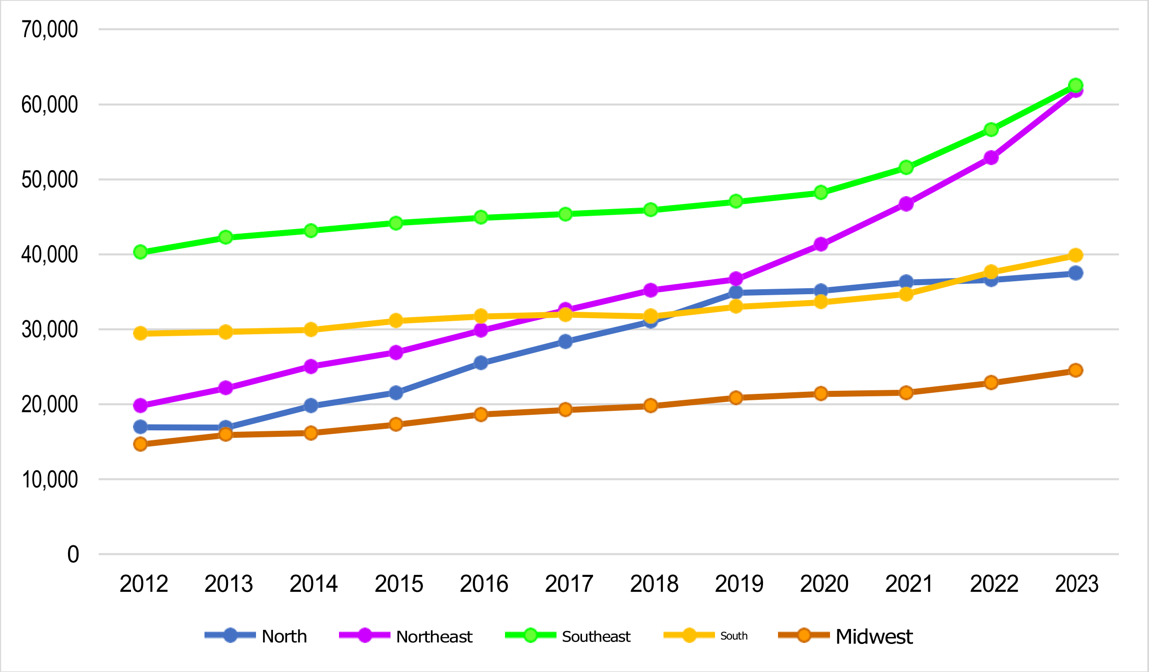
Considering that, in 2012, the total installed wind energy capacity in Brazil was of only 2.5 GW, which corresponded to 2% of the national electricity matrix, this variable will be analyzed considering all energy sources in the country.

Assigning a significance level of 5%, using the Mann-Kendall test , it is observed that there is statistical evidence of a trend, between the years 2012 and 2023, regarding the installed electricity capacity (MW) in all regions of Brazil.

Furthermore, through the Kruskal-Wallis test, it was observed that there is evidence of statistical difference in installed electricity capacity (MW) between regions of the country.

In this case, the Southeast region has greater installed capacity and the Midwest has less installed capacity.

Graph 8 – Installed capacity by region of Brazil (MW)



Source: Adapted from MME of Brazil 2012 – 2023.

It can be observed in Graph 8 that, on average, the largest installed capacity of electricity generation over the aforementioned period is highlighted in the Southeast region due to several factors. The first of these concerns the presence of large hydroelectric plants built to take advantage of the large amount of water falling from the rivers in the region.

According to Siffert Filho (2015), hydroelectric plants had, in 2014, a capacity installed of 24.5 GW, representing a significant portion of the national energy matrix. The region also had other sources, such as thermal, natural gas, biomass and sugarcane plants. -of-sugar.

The same author also listed different factors that contribute to this leadership until the year 2023. The Southeast had a robust transmission and distribution infrastructure of energy, facilitating the integration of new plants into the national electricity system and guaranteeing efficiency in supply, which characterized it as a region of high energy demand. In addition, there were government programs and financing, such as those offered by National Bank for Economic and Social Development (BNDES). These promoted investments in energy generation projects in this area, strengthening its capacity installed.

Through the multiple comparison test, it is observed that the North, Northeast and South regions are included in a second group with a higher average installed capacity in the referred period.

Table 8 – Installed capacity (MW) by region of Brazil

Region	Median	Average	SD	Coef. of determination (R)	Equation	Value -p	Value-p
North	29.672,50	28.335,75^{B}	7.966,51	95,25%	y= 2156,4x + 14319	**<0,001**	
Northeast	33.862,00	35.885,83^{B}	12.797,66	94,24%	y= 3445,7x + 13489	**<0,001**	
Southeast	45.595,50	47.624,58^{A}	6.398,76	82,34%	y= 1610,4x + 37157	**<0,001**	**<0,001**
South	31.811,50	32.827,58^{B}	3.197,66	86,34%	y= 824,06x + 27471	**<0,001**	
Center-West	19.492,00	19.371,42^{C}	2.988,22	98,46%	y= 822,42x + 14026	**<0,001**	

Source: Adapted from MME do Brasil 2012 – 2023.

Legend: (1) Mann-Kendall test; (2) Kruskal Wallis test; (3) Averages followed by the same letter do not differ statistically from each other.

Note: The Bonferroni test was applied at a significance level of 5%.

Regarding the North region, it was observed that the growth in capacity installed occurred with the construction and operation of plants such as Belo Monte (PA), Santo Antônio in Rondônia and Jirau (RO); as well as with the improvement in the transmission infrastructure of the National Interconnected System (SIN) in the region. These improvements were implemented between 2013 and 2019, allowing greater integration of the energy generated in this region, through the connection between the hydroelectric plants in the Amazon with Southeast (SE), Midwest (CO) and Northeast (NE). (Siffert Filho, 2014).

According to Siffert Filho (2014), Belo Monte, the largest electricity generation project implemented in the country and supported by BNDES, is the largest fully Brazilian hydroelectric plant, surpassing the Tucuruí Hydroelectric Plant. The author reported that the Belo Monte plant was completed in 2019, with a capacity of 11,233 MW. Together with the hydroelectric plants on the Madeira River (Santo Antônio and Jirau, which together have the capacity to generate 7,318 MW), they provided the consolidation of the Amazon's potential as a viable alternative from an energy point of view, economic, social and environmental for expanding the energy supply.

The development strategy for the North of Brazil, in addition to the implementation of an efficient network of efficient transportation, required the expansion of electricity generation, especially with the availability of this network for regional development. The reality, until 2010, was that this region was practically isolated from the rest of the country and, for this reason, it was fundamental its connection to the National Integrated System (Siffert Filho, 2014).

The Northeast region, in turn, received incentives from the Federal Government through the promotion of specific auctions for renewable energy. These boosted the installation of new wind and solar farms. Photovoltaic solar plants broke records in 2019, reaching peaks that supplied 10.3% of the region's electricity demand (Ciclovivo, 2019).

In mid-2019, this region became a leader in the generation of energy sources renewable, resulting from federal incentive policies, attracting investments and auctions, taking into account the favorable natural conditions for the generation of wind and solar energy. The investment in infrastructure made a difference for this region, which, also in 2019, added 744.95 MW to its installed capacity through the installation of 38 new parks wind farms distributed across the states of Bahia, Rio Grande do Norte and Maranhão (ABEEÓLICA, 2019).

With regard to the South region, it was observed that it also benefited from policies public policies that encouraged new energy installations. Although it is a region traditionally known due to hydroelectric plants and Small Hydroelectric Plants (SHPs), with emphasis on the Itaipu Plant, which is shared with Paraguay, the South has consolidated as one of the main wind energy centers in the country (Siffert Filho, 2014).

In summary, it can be inferred that the North, Northeast and South regions of the country underwent significant changes in its energy matrix in the period between 2012 and 2019, facilitating the emergence of public policies, investments in infrastructure and integration into the System National Interconnected. This fact is reflected in the improvement of the transmission infrastructure, in the North region, and consolidates the Amazonian energy potential, fundamental to minimize the historical isolation of the region (Siffert Filho 2014).

In the Northeast and South, renewable energy stands out. In the first, federal auctions are held in order to encourage the installation of wind and solar farms, making the

federal auctions in order to encourage the installation of wind and solar farms, making the region a leader in the sectors in 2019. (Ciclovivo, 2019; ABEEÓLICA, 2019). In turn, the South is traditionally dependent on hydroelectric plants and SHPs, and the Itaipu Plant stands out as the most relevant energy center. These changes reaffirm the importance of policies regional energy policies adaptable to the natural conditions of each location, in order to promote greater security and sustainable development.

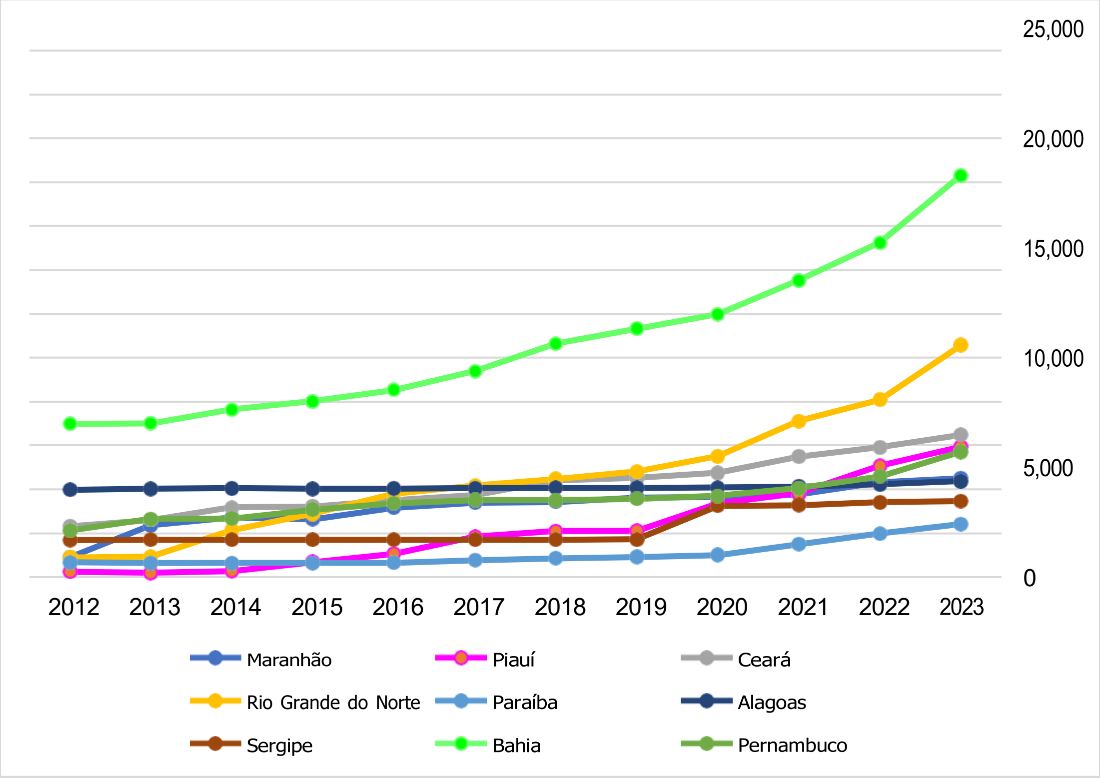
4.1.9 Installed Energy Capacity by states of Northeast Brazil

It is known that the Northeast region of Brazil stands out significantly in the national energy matrix, especially in relation to renewable sources. At the end of 2023, the total installed capacity of the National Interconnected System (SIN) reached 212,659 MW, in which the Northeast represented 25.8%, that is, 54,813 mw (Federal Government, 2023).

Given this scenario, the states of Bahia, Rio Grande do Norte and Ceará stood out in the development of an offshore wind matrix. For this reason, the results from the application of statistical inference pointed to the influence of these activities on the development of installed energy capacity in the region, as presented in Graph 9 and Table 9, below.

Attributing a significance level of 5%, using the Mann-Kendall test , it is verified that there is statistical evidence of a trend, between the years 2012 and 2023, regarding the installed electricity capacity (MW) in all states in the NE region. Furthermore, by means of the Kruskal-Wallis test, it is observed that there is evidence of statistical difference in the installed electricity capacity (MW) between the states of the Northeast. In this case, Bahia has the largest installed capacity and Paraíba the smallest installed capacity.

Graph 9 – Installed capacity by states of Northeast Brazil (MW)



Source: Adapted from MME do Brasil 2012 – 2023.

According to data from ANEEL (2023), this region is the main producer of wind energy in the country, concentrating 93% of the capacity related to this energy. In 2024, the wind sector supplied, for one minute, on July 23, 150% of the total demand of this region, which is positioned today with the largest installed capacity in the country (Gutierrez, 2023).

Bahia and Rio Grande do Norte stood out in terms of the evolution of the capacity of installed energy. The first state presents an expressive growth during the period highlighted. This phenomenon occurred mainly due to the expansion of wind generation and more recently by solar energy. Bahia proves to be an important center of energy renewable in the country given its wind potential in the semi-arid region and solar intensity (EPE, 2024).

This growth in the state of Bahia is strongly reflected in the incentive policies federal and auctions promoted by the National Electric Energy Agency (ANEEL) and the Ministry of Mines and Energy (MME) Bahia has become one of the national leaders in wind energy in specifically, responsible for almost 30% of the installed wind capacity in the country, according to data from ABEEÓLICA (2023). This was also possible due to its natural factors such as the occurrence of constant winds which attracted investors to the Bahian leadership in the sector.

Table 9 – Installed capacity by states in the Northeast of Brazil (MW)

State	Median	Average	Deviation standard	Coef. of determination nation (R	Equation	Value-p (1)	Value-p
Maranhão	3.408,00	3.207,33^{BC}	967,55	85,96%	y=248,81x + 1590	**<0,001**	
Piauí	1.964,00	2.225,33^{DC}	1.941,56	92,44%	y=517,72x - 1139,9	**<0,001**	
Ceará	4.066,50	4.175,25^{B}	1.318,45	97,70%	y=361,44x + 1826,1	**<0,001**	
Rio Grande do Norte	4.318,50	4.613,08^{B}	2.893,12	93,73%	y=776,81x - 436,35	**<0,001**	
Paraíba	821,00	1.059,58^{D}	594,45	72,34%	y=140,23x + 148,12	**<0,001**	**<0,001**
Pernambuco	3.505,50	3.544,67^{BC}	950,18	87,17%	y=246,02x + 1945,4	**<0,001**	
Alagoas	4.054,50	4.091,25^{B}	108,81	67,48%	y=24,779x + 3930,4	**<0,001**	
Sergipe	1.709,50	2.252,67^{DC}	811,11	69,56%	y=187,6x + 1033,4	**<0,001**	
Bahia	10.015,50	10.716,42^{A}	3.556,96	91,24%	y=942,31x + 4591,4	**<0,001**	

Source: Adapted from MME do Brasil 2012 – 2023.

Legend: (1) Mann-Kendall test; (2) Kruskal Wallis test; (3) Averages followed by the same letter do not differ statistically from each other.

Note: The Bonferroni test was applied at a significance level of 5%.

The state of Rio Grande do Norte, on the other hand, showed accelerated growth in relation to its considerable energy capacity, although lower than that of the state of Bahia. The state is a national leader national leader in installed wind capacity, a reflection of geographical factors, such as constant winds throughout the year, in addition to assiduous incentive policies, availability of flat areas for installation and improvements to the transmission grid. This characteristic positions the state as a region with a more concentrated energy profile, diverging from Bahia (EPE, 2024).

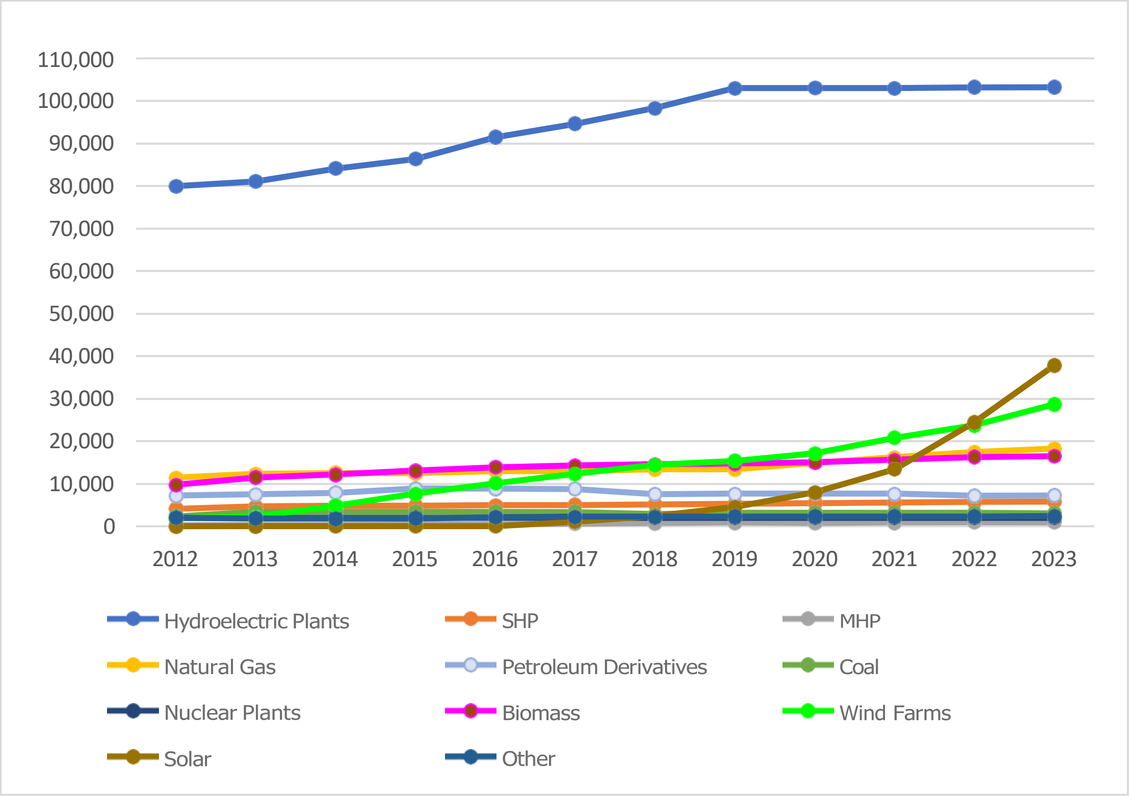
Finally, Piauí, despite disappointing as one of the states with the most accelerated growth, accelerated growth, due to its late entry into the market, the state has been standing out for the installation of solar farms, especially in the region of São João do Piauí, one of the largest complexes photovoltaic plants in Latin America. The Northeast reached peaks of 10.3% of regional demand supplied by solar energy, and Piauí was responsible for this expansion. (Ciclovivo, 2019)

4.1.10 Installed Energy Capacity by source in Brazil

In Graph 10, presented below, the behavior of the variable can be observed installed capacity by source, considering the period from 2012 to 2023. Assigning a level of significance of 5%, using the Mann-Kendall test, it is observed that there is evidence statistical evidence of a trend, between the years 2000 and 2023, regarding the installed capacity of electricity (MW). This refers to almost all types of generation, except that derived from oil, coal and nuclear power plants. In addition, through the Kruskal-Wallis test, it is possible to confirm evidence of statistical difference in installed electricity capacity (MW) between the types of generation, in which the hydroelectric plant has the highest capacity installed, followed by natural gas, biomass and wind power plants (see results in Table 10).

Throughout the period, hydroelectric plants remained the leader in the matrix Brazilian energy, with an installed capacity above 100,000 MW from the years 2000. However, the Graph also shows the diversification of the energy matrix, especially of wind and solar energy in recent years. (MME, 2023). Since 2012, a leap from from 2017, and in 2023, when its consolidation as the second most representative source is noted, there is a constant wave of policies and auctions promoted by the federal government, given the potential of the northeast region in particular. (ABEEÓLICA, 2023) The other sources, such as natural gas and other oil derivatives remained relatively stable or with moderate growth, which may indicate a gradual transition to other cleaner sources and renewable. (Ciclovico, 2019)

Graph 10 – Installed power capacity by source in Brazil (MW)



Source: Adapted from MME of Brazil 2012 – 2023.

Despite hydroelectric power being the largest source of generation in the country, the growth of wind power was cited by the Global Wind Energy Council (GWEC, 2022) report as virtuous, given its installed capacity, which jumped from 1 gigawatts to 21 gigawatts, from 2011 to January 2012. Therefore, wind energy was classified as the second largest source of energy generation in Brazil (Federal Government, 2022).

In 2022, according to EPE (2023), the share in installed capacity in Brazil of wind energy totaled 12.6%, and electricity production from this source reached 81.6 TWh, equivalent to an increase of 13% compared to the previous year, which reached 72.3 TWh. The installed capacity by generation source in Brazil, between 2012 and 2023, showed great growth, driven mainly by renewable sources. In 2012, the total capacity installed was approximately 121 GW and, in 2023, this number increased to 217GW, with the inclusion of distributed generation. Therefore, the distribution by source is as follows form: hydroelectric, 63.8%; thermoelectric, 15.9%; wind, 17.9%; and solar, 2.9%. The energy wind and solar stood out during this period. There is significant growth in relation to wind, which went from 1.5 GW in 2012 to 24.92 GW in March 2023 (MME, 2023).

Table 10 – Installed power capacity by source in Brazil (MW)

Type of generation	Median	Average	SD	Coef. of determi-nation - R)	Equation	Value-p	Valu-p
Plants Hydroelectric plants	96.474,50	94.284,92^{A}	9.322,40	91,67%	y=2475,6x + 78194	**<0,001**	
SHP	5.088,50	5.101,00^{C}	479,50	94,90%	y=129,54x + 4259	**<0,001**	
CGH	692,50	629,50^{F}	275,99	94,47%	y=74,369x + 146,21	**<0,001**	
Natural Gas	13.173,50	14.023,08^{B}	2.188,74	82,62%	y=563,62x + 10360	**<0,001**	
Derivatives of Petroleum	7.666,50	7.844,17^{C}	624,73	8,57%	y=-50,73x + 8173,9	**0,451**	
Coal	3.215,50	3.163,75^{D}	312,77	2,25%	y=13,023x + 3079,1	**0,090**	**<0,001**
Plant Nuclear	1.990,00	1.991,42^{E}	4,91	23,08%	y=-0,6538x + 1995,7	**0,147**	
Biomass	14.439,50	13.949,42^{B}	2.011,17	92,92%	y=537,67x + 10455	**<0,001**	
Plants Wind farms	13.347,50	13.266,58^{B}	8.472,77	98,04%	y=2326,8x - 1857,4	**<0,001**	
Solar	1.735,00	7.641,25^{CD}	12.054,98	67,20%	y=2740,7x - 10173	**<0,001**	
Others	2.232,00	2.150,08^{D}	204,70	74,75%	y=49,085 + 1831,1	**<0,001**	

Source: Adapted from MME do Brasil 2012 – 2023.

Legend: (1) Mann-Kendall test; (2) Kruskal Wallis test; (3) Averages followed by the same letter do not differ statistically from each other.

Notes: (1) SHP: Small Hydroelectric Plant; (2) CGH: Hydroelectric Generating Plant; (3) Others: coke oven gas, other non-renewables and other renewables. The Bonferroni test was applied at a significance level of 5%.

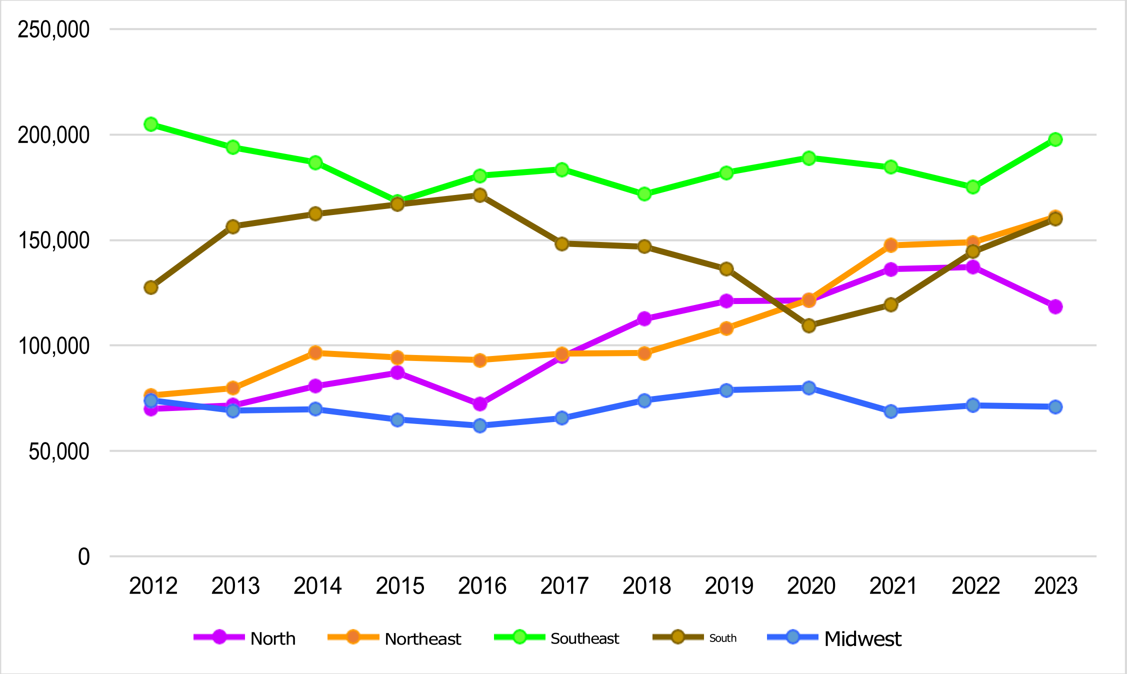
Furthermore, with the ABEEólica Annual Report (2023), the renewable energy industry in Brazil went through a decisive year in 2023, marked by the resumption of post-pandemic activities, the arrival of a new government and progress in planning for offshore wind energy. The same report highlights, however, that the sector faced challenges, such as a major blackout, which occurred in August, and difficulties in restoring power in São Paulo, highlighting the need for improvements in the reliability and flexibility of the electrical system.

Brazil gained international prominence by placing the energy transition at the center of its growth and diplomacy strategy, preparing to host the G20 presidency and the Clean Energy Ministerial in 2024; in addition to COP30, which takes place in Belém, in 2025. This should focus on nature conservation and implementation (ABEEÓLICA, 2024).

4.1.11 Energy generation by region in Brazil

Regarding the distribution of energy generation among the country's regions, the following is observed: following scenario, as presented in Graph 11 below.

Graph 11 – Energy generation by region in Brazil (GWh)



Source: Adapted from MME of Brazil 2012 – 2023.

Analyzing the variable of electricity generation by region and assigning a significance level of 5%, using the Mann-Kendall test, it is clear that there is statistical evidence of trend, between the years 2012 and 2023, regarding electricity generation (GWh) in the North and Northeast. Furthermore, using the Kruskal-Wallis test, it is possible to observe evidence of statistical difference in electricity generation (MW) between the regions of Brazil. The Southeast region has the highest electricity generation and the Midwest has the lowest electricity generation.

The inferential behavior obtained from this variable is described in Table 11, whose Valor-p results from the Mann-Kendall test for the Southeast, South and Midwest regions were adverse to those presented by the North and Northeast regions, which present prospects for expansion of energy generation through the wind power matrix. In July 2023, the Northeast established new wind production records with instantaneous generation, reaching 18,401 MW, a milestone that corresponded to 149% of the region's demand at that time.

Thus, the Brazilian energy matrix stands out for the diversity of generation sources, especially with renewables. With regard to the North region, it is possible to observe the abundance of water resources, as it houses several hydroelectric plants and offers energy to the System Interconnected National as a whole. Regarding the year 2022, its installed generation capacity was 25,326 MW. Of these, 11.6% represent the total capacity of Brazil (EPE, 2023).

Table 11 – Energy generation (GWh) by region of Brazil

Region	Median	Average	SD	Coef. of determi-nation R	Equation	Value-p	Value-p
North	103.677,50	101.945,75^{C}	25.392,00	84,21%	y=6462,5x + 59939	**<0,001**	
Northeast	96.472,00	109.960,42^{C}	28.282,87	86,95%	y=7314,5x + 62416	**<0,001**	
Southeast	183.963,00	184.807,67^{A}	10.609,66	3,93%	y=-583,29x + 188599	**0,732**	**<0,001**
South	147.515,50	145.748,00^{B}	19.401,62	8,44%	y=-1563,5x + 155911	**0,373**	
Center-West	70.332,50	70.729,67^{D}	5.366,05	7,38%	y=404,41x + 68101	**0,537**	

Source: Adapted from MME of Brazil 2012 – 2023.
Legend: (1) Mann-Kendall test (2) Kruskal Wallis test (3) Averages followed by the same letter do not differ statistically from each other.
Note: The Bonferroni test was applied at a significance level of 5%.

The Midwest region has significant potential for solar energy, as the region receives a high incidence of annual solar radiation. Goiás and Mato Grosso invest significantly in the expansion of the source, whether in large port plants or in generation distributed. In 2022, it represented 7.8% of the country's total. In general, the region represents a smaller participation in the national energy profile, concentrating small hydroelectric plants and thermoelectric plants (EPE, 2023).

The Northeast, in turn, has consolidated itself as a hub for renewable energies, especially solar and wind. The region also had the largest proportional growth of the decade in generation of non-hydroelectric energies. This advance was evidenced due to public policies of incentive, auctions for renewable sources, in addition to its favorable geographical characteristics. Bahia and Rio Grande do Norte are the ones that stand out in relation to these sectors (MME, 2023).

With regard to the Southeast, this result is justified because it is classified as the region that consumes the most electricity. This represents 50% of the SIN's load in 2013. In this scenario, the water source stands out due to the abundance of this resource, exemplified mainly by the Furnas and Ilhas Solteiras hydroelectric plants, in addition to the strategic use of thermoelectric plants to guarantee stability in times of drought (EPE, 2023).

Regarding the South of the country, it is clear that it remained the second largest generator of energy in the country, with emphasis on the hydroelectric source, especially in the states of Paraná and Santa Catarina. According to data from the Brazilian National Energy Balance (BEN), between 2012 and 2023, generation was from 80,000 GWh to 88,000GWh. Furthermore, in the South, the participation of wind energy and photovoltaic solar energy was considerably inserted, and presented a diversification in its energy matrix (ANEEL, 2023).

Finally, with regard to the North of the country, this statistical behavior corroborates the fact that, in this region, there is a concentration of large hydroelectric plants, such as Tucuruí (PA), Samuel (RO) and Belo Monte (PA). In relation to energy generation, it is observed that, from 2012 to 2022, there was a considerable growth from 42,000 GWh to 56,000 GWh (EPE, 2023).

However, there was no diversification of the energy matrix in this region, remaining exclusively hydroelectric, without the inclusion of renewable sources. Consequently, it creates energy dependence on climatic conditions in these plants, in addition to difficulties in energy transmission (ANEEL, 2022).

4.1.12 Energy generation by states in the Northeast of Brazil

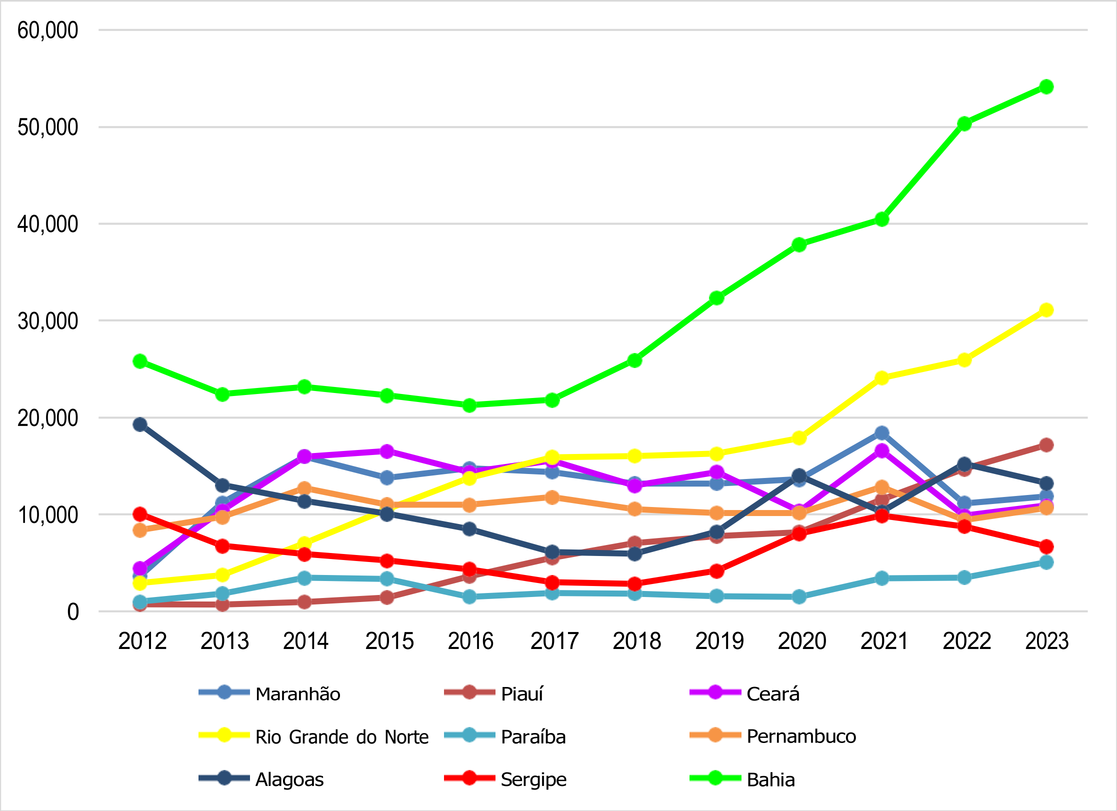
The largest energy generation in the period between 2012 and 2023, statistically, in the Northeast, points to the prominence of the state of Bahia. This was identified as the leader in energy generation in Brazil, mainly due to the expansion of sources renewables, especially wind and solar.

Attributing a significance level of 5%, using the Mann-Kendall test, there are statistical evidence of a trend, between the years 2012 and 2023, regarding electricity generation (GWh) in Piauí, Rio Grande do Norte and Bahia.

Furthermore, using the Kruskal-Wallis test, there is evidence of a difference statistical electricity generation (GWh) between the states of the Northeast. In this case, Bahia has the highest electricity generation and Paraíba the lowest electricity generation.

According to Lages (2024), Rio Grande do Norte, Bahia and Piauí were the largest wind energy producers. Rio Grande do Norte leads this ranking with 248 parks and 7,872.43 MW of power. Bahia occupies second place, with 276 parks and 7,633.37 MW; while Piauí is third, with 108 parks and 3,583.95 MW. The main factors that develop in this scenario include geographical and climatic characteristics ideal for generation of wind energy. Especially inland and on the coast, there are constant and strong winds.

Graph 12 – Energy generation by states in the Northeast region (GWh)



Source: Adapted from MME of Brazil 2012 – 2023.

The states that stood out the most in relation to the infrastructure variable in the Northeast were: Bahia, Rio Grande do Norte and Maranhão. The first is the state with the highest total electricity generation in the Northeast. The main reasons for this are the high potential wind power in the interior of the state, strong solar irradiation and the presence of thermal power plants. Wind power presents itself as the protagonist in this process, more specifically onshore, followed by solar energy, with significant installations in recent years (EPE, 2023).

Rio Grande do Norte, in turn, is considered the leader in onshore wind generation in the Northeast, obtaining 95% of its energy production from winds. It also has very facilitating geographical characteristics for this energy matrix, such as winds constant and regular, which guarantees sufficient capacity factors. Factors like these, combined with private incentives for adequate structuring, have made the state a wind power center Brazilian, highlighting it in electricity generation (MME, 2023).

Table 12 – Energy generation by states in the Northeast region (GWh)

State	Median	Average	SD	Coef. of determi-nation (R	Equation	Value-p	Value-p
Maranhão	13.421,50	12.933,50^{B}	3.574,31	12,73%	y=353.66 + 10635	**0,945**	
Piauí	6.310,00	6.617,33^{C}	5.575,56	93,46%	y=1494.9 - 3099.5	**<0,001**	
Ceará	13.650,00	12.692,25^{B}	3.626,66	1,76%	y=133.41 + 11825	**0,945**	
RN	15.987,00	15.443,00^{B}	8.682,03	95,71%	y=2355.7 + 131.13	**<0,001**	
Paraíba	1.874,50	2.496,92^{D}	1.221,49	26,76%	y=175.2 x + 1358	**0,150**	**<0,001**
Pernambuco	10.632,00	10.708,42^{B}	1.295,28	2,23%	y=53.654 + 10360	**1,000**	
Alagoas	10.815,00	11.271,92^{B}	3.919,05	1,39%	y=-128.1 + 12105	**0,837**	
Sergipe	6.299,00	6.300,08^{C}	2.499,66	1,27%	y=78.077 + 5792.6	**0,837**	
Bahia	25.863,50	31.496,83^{A}	11.645,21	75,05%	y=2798 + 13310	**<0,007**	

Source: Adapted from MME do Brasil 2012 – 2023.

Legend: (1) Mann-Kendall test; (2) Kruskal Wallis test; (3) Averages followed by the same letter do not differ statistically from each other.

Note: The Bonferroni test was applied at a significance level of 5%.

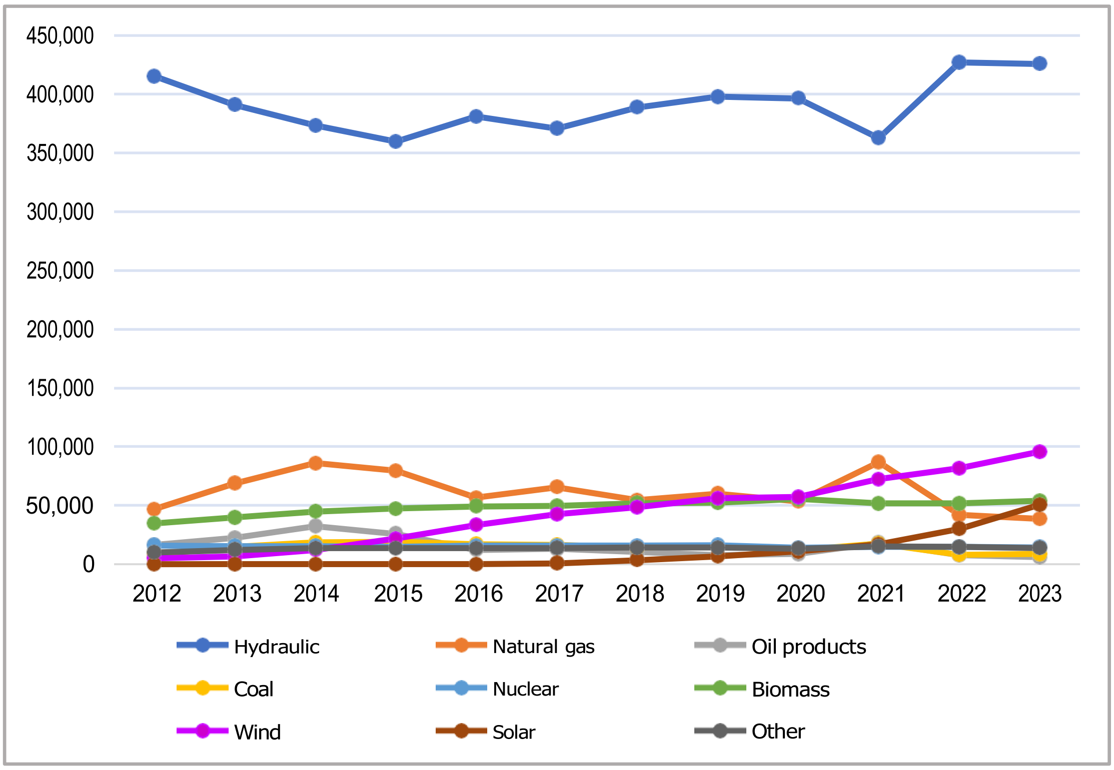
Maranhão demonstrates a distinct energy profile from the others, as it has thermoelectric and liquid fuel generation as predominant in its matrix. The state has less participation in non-hydro renewable sources, compared to Bahia and Rio Grande do Norte. However, this does not mean that there is no potential, it just hasn't been explored yet. This energy matrix is justified due to the location and availability of gas via infrastructure of the Parnaíba Basin. In short, renewable sources in the region are still in very incipient phases (EPE, 2024; ANEEL, 2023)

4.1.13 Energy generation by source in Brazil

Assigning a significance level of 5%, through the Mann-Kendall test, there are statistical evidences of trend, between the years 2012 and 2023, regarding the generation of electric energy (GWh) in almost all types of generation, except in hydraulic, natural gas, coal and nuclear.

Furthermore, through the Kruskal-Wallis test, evidence of statistical difference in electrical generation (GWh) between the types of generation can be found. In this case, the plant hydroelectric has the highest electricity generation, followed by natural gas, biomass and wind power plant.

Figure 13 – Energy generation by source in Brazil (GWh)



Source: Adapted from MME of Brazil 2012 – 2023.
Notes: (1) Includes PCH (Small Hydroelectric Plant), CGH (Hydroelectric Generating Plant) and self-production; (2) Petroleum derivatives: diesel oil (includes biodiesel) and fuel oil;
(3) Biomass: firewood, charcoal, sugar cane bagasse and lye; (4) Others: coke oven gas, other non-renewable and other renewable.

Natural gas, even though it is a component derived from non-renewable sources, is in second position, in this category, in terms of energy supply, in the year 2023, behind only oil and its derivatives, according to the annual report of the National Energy Balance of 2024. The natural gas produced in Brazil is mostly associated with oil, destined for electricity generation, process heat production and direct heating in the most diverse economic activities, in addition to being used as raw material (non-energy use) in the petrochemical and fertilizer industry (EPE, 2020b).

Throughout the historical series, its participation remains in second place, in regarding non-renewable sources. Among the main factors for this position is the fact that be considered a cleaner energy source compared to other fuels fossil fuels, such as coal and fuel oil. Its burning results in reduced emissions of carbon dioxide (CO_2) and other pollutants, making it an attractive option for energy generation in a context of growing environmental concern.

Table 13 – Energy generation by source in Brazil (GWh)

Type of generation	Median	Average	SD	Coef. of determi-nation (R	Equ tion	Value-p	Value-p
Hydraulic	389.981,50	$390.874,17^{A}$	22.936,31	11,62%	y=2168.2x + 376781	**0,373**	<0,001
Natural Gas	58.369,00	$61.551,50^{B}$	16.263,55	12,52%	y=-1596.2 + 71927	**0,150**	
Derivatives of Petroleum	12.559,00	$15.010,75^{C}$	8.217,74	46,69%	y=-1557.4 + 25134	**0,007**	
Coal	15.064,00	$14.148,50^{C}$	3.967,59	11,33%	y=-370.37 + 16556	**0,244**	
Nuclear	15.414,00	$15.235,58^{C}$	692,39	34,56%	y=-112.92 + 15970	**0,064**	
Biomass	50.548,00	$48.528,33^{B}$	6.087,70	75,22%	y=1464.3x + 39010	**<0,001**	
Wind	45.424,00	$44.382,25^{B}$	29.805,13	98,36%	y=8198.5x - 8908.1	**<0,001**	
Solar	2.146,00	$9.944,83^{C}$	15.773,62	66,56%	y=3569.3 x - 13255	**<0,001**	
Others	13.777,50	$13.515,08^{C}$	1.330,90	54,01%	y=271.31x + 11752	**0,007**	

Source: Adapted from MME do Brasil 2012 – 2023.

Legend: (1) Mann-Kendall Test; (2) Kruskal Wallis Test; (3) Averages followed by the same letter do not differ statistically from each other.

Notes: (1) Includes PCH (Small Hydroelectric Plant), CGH (Hydroelectric Generating Plant) and self-production; (2) Petroleum derivatives: diesel oil (includes biodiesel) and fuel oil; (3) Biomass: firewood, charcoal, sugarcane bagasse and lye; (4) Others: coke oven gas, other non-renewables and other renewables. The Bonferroni test was applied at a significance level of 5%.

Another relevant factor was the implementation of public policies and the creation of a favorable regulatory framework, such as the New Gas Law, in 2021. These policies aimed to liberalize the natural gas market in Brazil, in order to achieve increased competitiveness, reduced prices and attract investments to the sector, stimulating the use of natural gas in the national energy matrix (Gutierrez, 2022).

During this period, there were also significant investments in the expansion of natural gas transportation and distribution infrastructure, including the construction of gas pipelines and Liquefied Natural Gas (LNG) regasification terminals. This expansion facilitated access to natural gas in several regions of the country, promoting its use in industrial sectors and in electricity generation.

Another aspect that influenced the position of natural gas in this period was the flexibility operational of natural gas thermoelectric plants. This is a crucial characteristic for the energy security of the country, especially during water crises, which allows these plants to be activated quickly, should there be energy demand in periods of low hydroelectric generation or other renewable sources. The combination of these factors reinforced the second position of natural gas throughout this period, as a strategic energy source in the country.

Biomass generation is statistically, on average, among the largest sources of energy producers, due to some results over the period described. Production from biomass in 2020 reached 55.60 TWh, corresponding to 9% of electricity supply in Brazil (Nogueira; Capaz; Lora, 2021).

This represented the maintenance of the generation of 2018. In 2023, energy generation from biomass-fired thermoelectric plants grew 4% compared to 2022, reaching 53.854 TWh. During this period, biomass consolidated itself as the third largest source of energy electricity for the National Interconnected System (SIN), behind only hydroelectric plants and wind farms. Finally, in 2023, a record energy production was obtained from biomass 3,218 average megawatts (MW), which corresponded to 4.6% of all energy demand consumed in the country. (Eixos, 2024)

One of the factors that strengthened energy production from biomass was the fact that Brazil is one of the largest producers of this source, considering mainly sugar cane bagasse sugar, agricultural waste, firewood and lye. In this sense, it is worth mentioning that, in in relation to the internal energy supply in the country, 16.9% was attributed to sugarcane biomass in a matrix of renewable supply of 49.1% at the end of 2023 (Ben, 2024). This evolution reflects the finding of what was statistically verified and presented in Table (13).

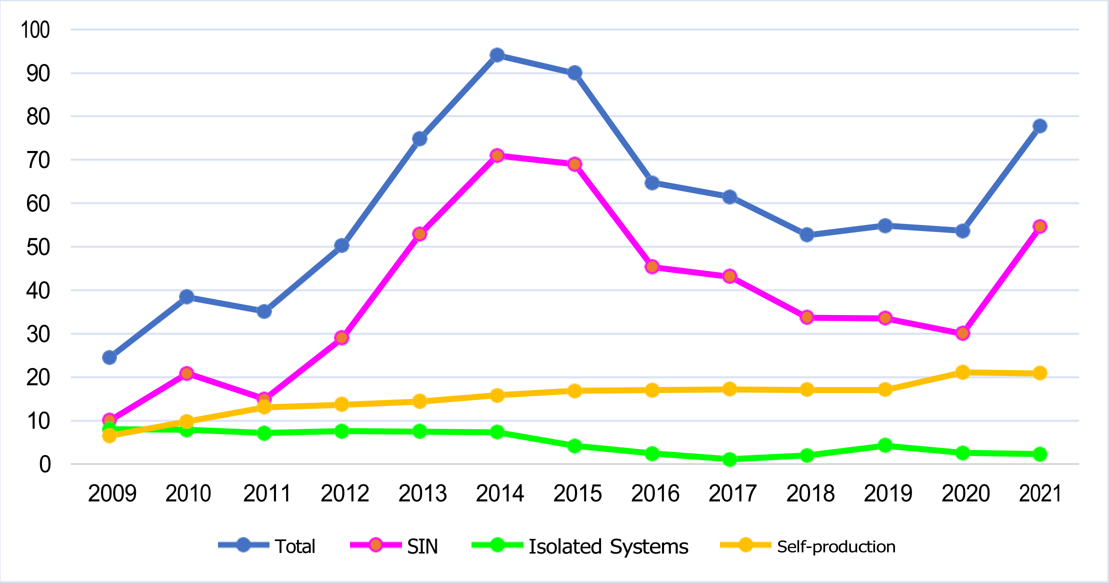
4.1.14 GHG emissions from energy generation in Brazil

The polluting aspect of energy can be divided by the generation sources that we find in the national territory, which have distinct and detailed characteristics, as described by the Ministry of Mines and Energy (MME). The period analyzed in this study refers to the time interval of 2012-2023, described below.

In this sense, attributing a significance level of 5%, using the Mann-Kendall, there is statistical evidence of a trend, between the years 2009 and 2023, regarding the types of GHG emissions from Electricity Generation from isolated systems and self-production.

Furthermore, through the Kruskal-Wallis test, there is evidence of difference statistical types of GHG emissions from Electricity Generation, in which the SIN presents higher gas emissions.

Chart 14 – GHG emissions from power generation in Brazil – MtCO2



Source: Adapted from MME of Brazil 2009 – 2023.
Notes: (1) Mann-Kendall test; (2) Kruskal Wallis test; (3) Averages followed by the same letter do not differ statistically from each other; (4) Bonferroni test was applied at the 5% significance level.

Starting with the country's main power transmission grid, the SIN is predominantly supplied by renewable sources, especially hydroelectric plants, which represent about 60% to 70% of the installed capacity. However, in periods of drought or low water availability, the activation of thermoelectric plants powered by fossil fuels (gas natural gas, coal, diesel oil) contributes to significantly increased GHG emissions significantly (EPE, 2023).

Considering the changes that have occurred in Brazil's electricity matrix from 2009 to 2023, the following stand out: the growth of plants, both in number and in capacity installed capacity of thermoelectric parks; the increase, due to the need to guarantee security energy to the SIN, of the installed capacity of fossil thermal plants (natural gas, coal, oil diesel and fuel oil); and the expressive growth of renewable sources, such as biomass and biogas. Emissions in the SIN system showed highs in dry periods, but with less intensity due to the use of natural gas.

With regard to the type of emission emitted by isolated systems, electricity generation in these areas are highly dependent on fossil fuels, which results in significant emissions of GHG. This is because isolated systems are regions of Brazil not connected to the System National Interconnected (SIN), located mainly in the Legal Amazon. The matrix energy was dominated by diesel oil, followed by fuel oil and natural gas. In the period from 2009 to 2021, there was an increasing trend in emissions due to the growth of energy demand. Many localities remained isolated due to difficulties logistics. In addition, there was a delay in replacing fossil fuel power plants with renewable sources (solar and biomass). As a result, emissions remained high. In this sense, there were GHG emissions from self-production (electricity generation carried out by companies for consumption own, in industrial sectors such as steel, pulp and paper, mining and chemicals).

Table 14 – GHG emissions from energy generation in Brazil – MtCO2

Types of emission	Median	Average	SD	Coef. of determination nation (R	Equation	Value -p	Value -p
Total	54,80	59,40	20,78	19,32%	Y=2.345x + 42.979	**0,161**	
SIN	33,70	39,07^{A}	19,17	15,98%	Y=1.9676x + 25.288	**0,246**	
Systems isolated	4,20	4,94^{C}	2,67	73,37%	Y=-0.5581: +9.0454	**<0,001**	**<0,001**
Self-production	16,80	15,40^{B}	4,04	86,46%	Y=0.9656x + 8.6452	**<0,001**	

Source: Adapted from MME do Brasil 2012 – 2023.

Notes: (1) Mann-Kendall test; (2) Kruskal Wallis test; (3) Averages followed by the same letter do not differ statistically from each other; (4) The Bonferroni test was applied at a significance level of 5%.

It is also worth mentioning the concentration of the electricity system in Brazil. According to IEMA (Energy and Environment Institute, 2022), electricity generation in 2022 was produced in only five states: Rio de Janeiro, Amazonas, Maranhão, Santa. In this case, were 76% of the country's energy was produced, influencing the use of other less controlled systems, that is, polluting power plants. This scenario contributes to a scenario of more emissions of local atmospheric pollutants.

Finally, GHG emissions from self-production (electricity generation carried out by companies for their own consumption, in general, in industrial sectors) stand out. This system of energy distribution, due to its more industrial nature, operates using fuels fossil fuels, such as natural coal, fuel oil, among others. Therefore, they benefit from operate with less demanding environmental standards, which increases GHG emissions per unit generated. Consequently, there is a higher emission pattern than that of national average.

The second place position in rankings of gas emissions from generation self-production electricity raises awareness and makes it possible to pay attention to the medium and long term, taking into account a plan to use gas-fired power plants. In addition, there is a reduction in the use of plants to coal or even the discontinuation of this energy distribution mechanism, taking into account the guarantee of energy availability at low cost and in a sustainable way.

Therefore, reducing GHG emissions and achieving the COP 28 goals in the short term; and the Paris Agreement in the long term; puts the electricity sector in a delicate position, since achieving a one hundred percent renewable matrix requires considerable investment.

4.2 Second stage of the study

As defined previously, a linear regression model is characterized by the ability to identify approximately linear relationships between two or more variables. A From this model, it is possible to draw conclusions about factors involved in phenomena that cannot be directly observed in reality. In this context, the parameters population β are estimated from a sample, using the Ordinary Least Squares (OLS) method. The resulting equation reflects the phenomenon studied, allowing the identification of the relationships between the variables.

In the present study, the dependent variable analyzed was the cost of energy generation CAPEX (C), while the independent variables were: installed power (POT), area of the park (AP), maximum depth of the wind turbines (F), distance to the coast (D) and export cable length (L), respectively (Y 1 ,...,Ym) and the (Xi1,...,Xik).

To ensure that the estimated parameters (βk) are not biased, but efficient and consistent, it is necessary to meet certain assumptions related to the variables independent (Xi1,...,Xik), to the residuals and to the specification of the model.

The first assumption requires that the independent variables do not present random disturbances or linear correlations between them. The second requires that the residuals obey the hypotheses of constant variance, normality and absence of autocorrelation. For Finally, it is essential that the model includes only significant independent variables and that the scales of the variables are defined, preserving the linearity of the model (Dantas, 2003).

The explanatory power of the multiple regression model was evaluated using the adjusted coefficient of determination (R² adjusted), which indicates the proportion of variability in cost explained by the independent variables. As reported in the studies carried out by Gujarati and Porter (2008), the use of this coefficient is widely accepted because this correction allows comparing models with different numbers of independent variables.

The application of Multiple Linear Regression, performed using the program computational R, was done in order to verify the results of the regression. The results of the estimates found are presented in Table 15, considering three distinct models namely:

- Model 1 – A sample of 50 offshore parks and 5 independent variables;
- Model 2 – A sample of 50 offshore parks and 4 independent variables;
- Model 3 – A sample of 49 offshore parks and 4 independent variables;

Table 15 – Results of Regression Models 1, 2 and 3

Model 1	Coefficients	p-Value		Observations	50
Intercept	0,000000017	<0,05		R^2	1,0
Ap (km²)	0,000000000004	0,373		Adjusted R	1,0
L (km)	0,000000000003	0,526		Standard error residual	0,000000006089
F (km)	- 0,000000026	0,451		F statistic	4.707E^+31
Pot (kw)	12249,99	<0,05			
D (km)	-0,00000000002	0,733		P-value (< 0,05)	<0,05
Model 2	Coefficients	p-Value		Observations	50
Intercept	12118161	0,00215		R^2	0,5296
Ap (km²)	26877	0,00000866		Adjusted R	0,4878
F (km)	- 65979318	0,22097		Standard error residual	9550000
D (km)	- 2421	0,97857		F statistic	12,67
L(km)	2745	0,58925		P-value (< 0,05)	5.516 E-07
Model 3	Coefficients	p-Value		Observations	49
Intercept	17,179	< 0,05		R^2	0,8109
1/[Ap (km²)]^0,5	-9,749	< 0,05		Adjusted R	0,7937
Ln [F (km)]	-0,0238	0,816		Standard error residual	0,3623
D (km)	-0,0022	0,524		F statistic	47,16
L(km)	0,00055	< 0,05		P-value (< 0,05)	< 0,05

Source: Research data applied to R software.

Model 1 was initially measured using all the study variables and their functional forms considered as linear. The results were detailed in Table 15.

The explanatory power of the multiple regression model was assessed using the adjusted coefficient of determination (adjusted R^2), which indicates the proportion of variability in the costs explained by the independent variables.

The calculated coefficient was 1, announcing that 100% of the variation in CAPEX costs of the projects can be explained by the variables included in the model. The result displayed indicates the existence of error in the data.

The aforementioned error was caused by the fact that the COST variable was calculated as a function of the POT variable, making the regression redundant, and for this reason, the POT variable was eliminated from Model 1, and this new model was then called Model 2, in order to be re-evaluated.

The result of Model 2 created, without including the POT variable, is also described in Table 16. And for the analysis of the model's residuals, the following graphs were subsequently plotted: Residuals vs Fitted, Q-Q plot, Scale-Location (Homoscedasticity), and Cook's distance, whose results are disclosed in Figure 21.

The Residuals vs Fitted graph revealed a concentration of points on the left, suggesting heterogeneity of variance, which indicates that the assumption of homoscedasticity was not met. For confirmation, the Breusch-Pagan test was performed, which presented a probability of 0.003363787, lower than the adopted significance level (5%) (See annexes).

Given this finding, the null hypothesis H 0 was rejected, confirming the presence of heteroscedasticity in the model in question.

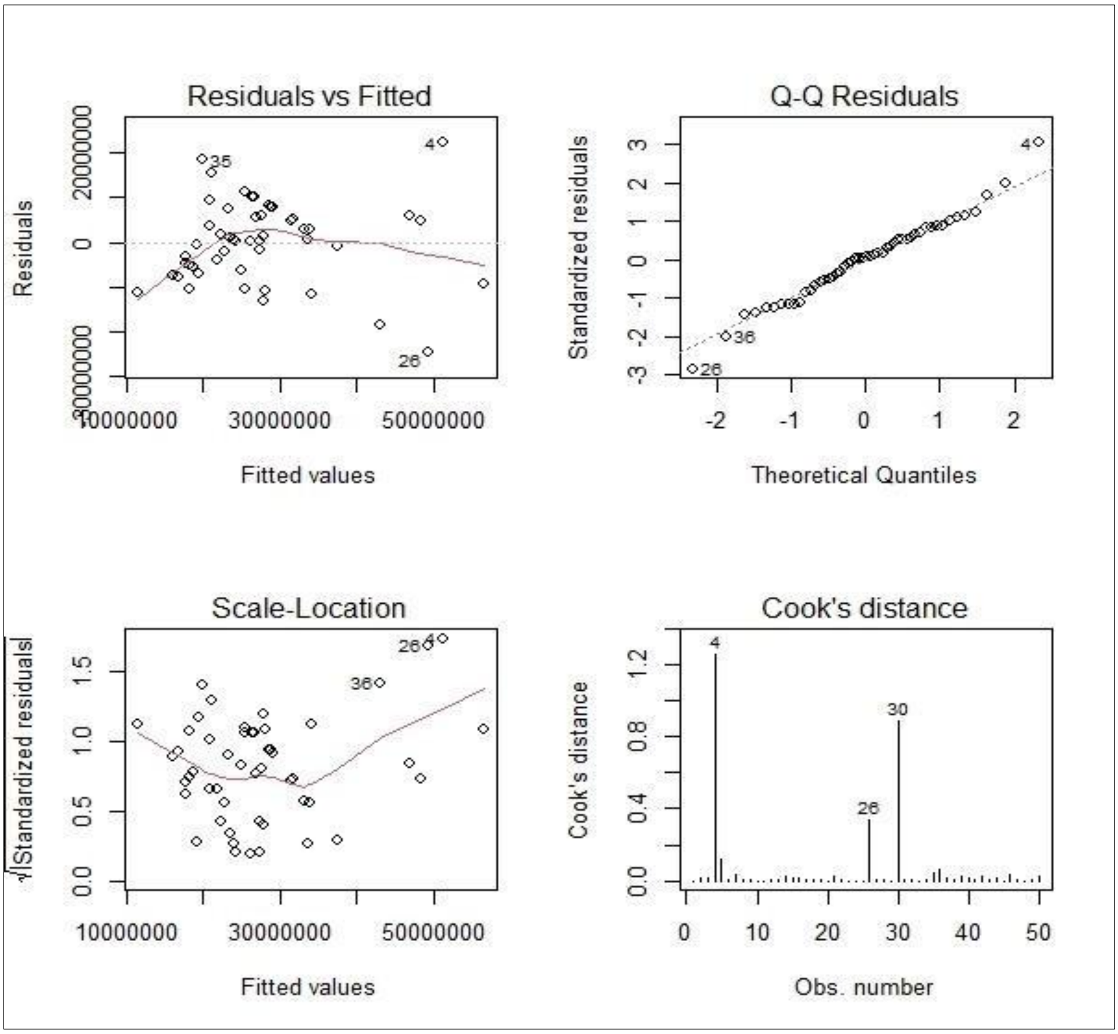
The assumption of normality of residuals was also evaluated. Initially, the Q-Q plot graph (Figure 21) was analyzed, which revealed that the quantiles of the distribution of residuals do not align perfectly with the reference line, suggesting non-normality of the residuals.

To corroborate this observation, the Kolmogorov-Smirnov test was applied, which resulted in a p-value of 0.9280, greater than 5%, which led to the rejection of the normality hypothesis. Thus, with a confidence level of 95%, it is observed that there is evidence that the residuals do not follow a normal distribution.

To verify the absence of autocorrelation, the residuals were analyzed through the graph of residuals versus the adjusted values (Figure 21). The Durbin-Watson statistical test was applied. This test assesses the presence of autocorrelation in the residuals of a regression, considering the hypotheses H 0 (no autocorrelation) and H a (there is autocorrelation). The p-value obtained was 0.7865, greater than 0.05, leading to the acceptance of the null hypothesis of absence of autocorrelation.

This result confirms that Model 2 meets the assumption of no autocorrelation, being considered unbiased, efficient, and consistent.

Figure 21 – Graphical result of the tests applied to Model 2



Source: Research data.

The other assumption for the application of OLS in the calculation of estimated parameters is that the independent variables do not present linear relationships with each other. In this sense, the correlation matrix was applied, a tool that can be used to identify such relationships displayed in Figure 22.

The analysis of Figure (22) reveals that the greatest correlation is occurring between the variables independent: export cable length (L) and park area (AP). However, the value not above 0.70 could be classified as strong moderation. In this case, the study variables were maintained, and the assumption of absence of autocorrelation of the independent variables was met.

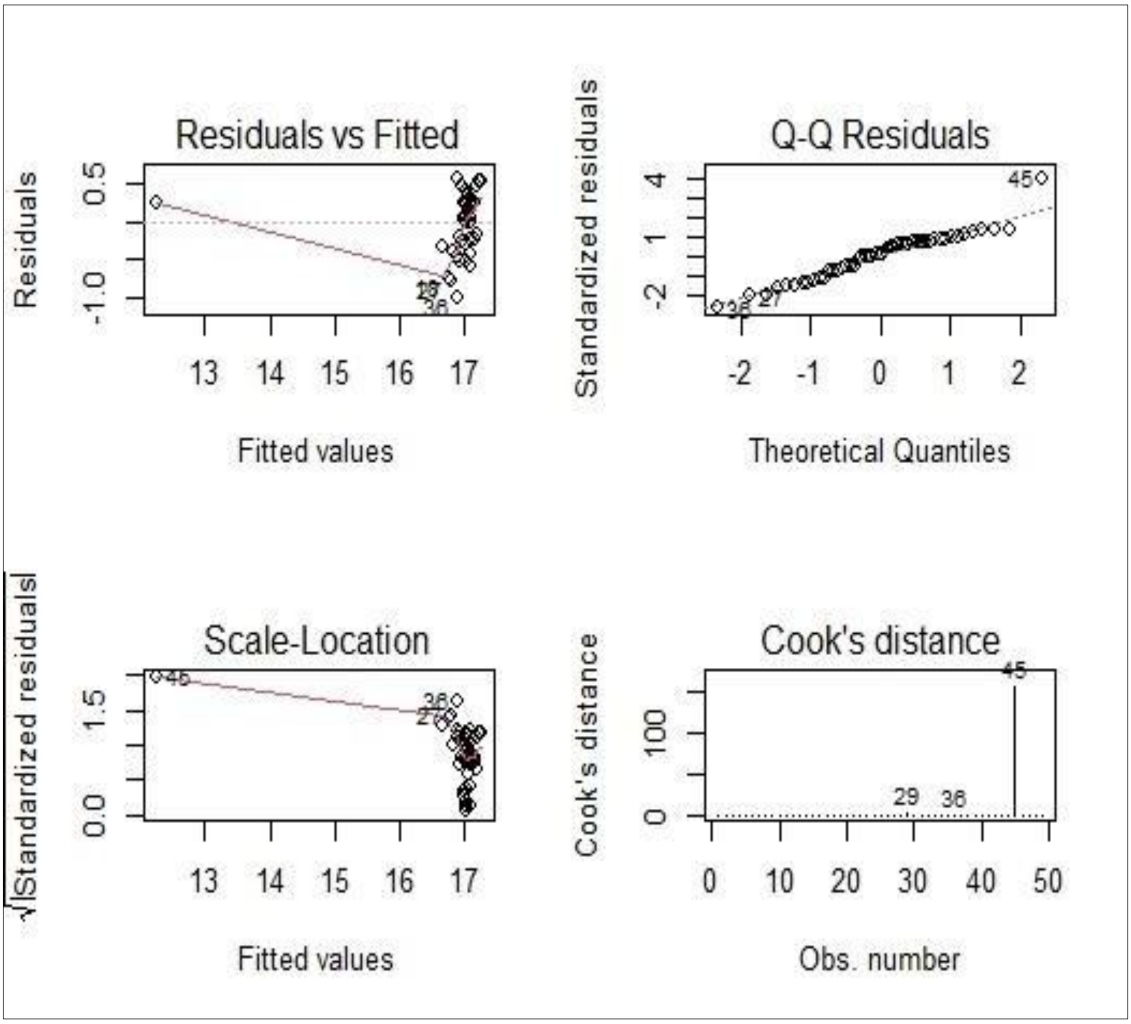
Figure 22 – Correlation matrix of the variables

Source: Self-authored.

To improve the model, the natural logarithm was applied to the variable F and the inverse function of the square root to the variable AP, as these specifications were better suited to the variables in question. In addition, data 46 was removed from the sample, which corresponds to the park at the site of tests of SENA/RN, which is exposed in an area very different from the other parks listed in this study. The mentioned change resulted in the model called Model 3, and new results were obtained and also displayed in Table 16. This procedure caused the observation of some changes in relation to Model 2, whose results are presented in Figure 23.

The Residuals vs Fitted pronounced graph revealed a concentration of points to the right, suggesting heterogeneity of variance, which indicates that the hypothesis of homoscedasticity was not met. To confirm this result, it was carried out, again, the Breusch-Pagan test, which presented a probability of 0.9981872, higher than the level of significance adopted (5%). Given this result, the null hypothesis H 0 was accepted, indicating that the model is homoscedastic. This notification corroborates the intuition that there is an outlier in the sample that pronounced this behavior.

Figure 23 – Graphical result of the tests applied to Model 3



Source: Source: Research data.

The hypothesis of normality of the residuals was also evaluated. Initially, it was analyzed the Q-Q plot (Figure 23), which revealed that the quantiles of the residual distribution align approximately on top of the reference line, suggesting the non-normality of the residuals. To corroborate this observation, the Kolmogorov-Smirnov statistical test was applied, which resulted in a p-value of 0.1868, greater than 5%, leading to the rejection of the hypothesis of normality. Thus, with a confidence level of 95%, there is evidence that the residuals do not follow a normal distribution. Considering the existing limitations in the test, the option for the interpretation of the Q-Q-plot graph for the final evaluation of residual normality was adopted.

The absence of autocorrelation between the residuals was performed by analyzing the residual plot versus adjusted values (Figure 23), in addition to the Durbin statistical test-Watson . This test evaluated the presence of autocorrelation in the residuals, as described previously, considering the hypotheses H0 (no autocorrelation) and Ha (autocorrelation). The p-value obtained was 0.5912, higher than 0.05, leading to the acceptance of the null hypothesis of absence of autocorrelation. This result confirms that the model meets the assumption of no autocorrelation, being considered unbiased, efficient and consistent.

The absence of statistical significance in the individual test of the coefficient in two variables can be justified by factors such as a small real effect of the independent variable on the dependent variable or the possible omission of relevant variables, which could be absorbing part of the model's explanation. In addition, a relatively high standard error may have reduced the t-statistic, making it difficult to reject the null hypothesis, although the variable has some impact on the response variable.

Thus, the interpretation of the results should not be based exclusively on statistical significance, but also on the theoretical basis and coherence of the model as a whole, ensuring that the inclusion or exclusion of variables considers both robustness statistical as well as the conceptual validity of the analysis.

Finally, reporting Model 3, the RLM analysis showed that the park area and the cable length has effects on the cost (CAPEX). The analysis of Model 3 suggested a relationship of these variables based on a log-linear modeling, allowing to analyze the elasticity and the proportional effects between these variables, with the following result: an increase of one unit of measure of the cable length results in an approximate change of 0.05% in the park's Cost (CAPEX).

The park area variable as a function of cost (CAPEX) resulted in an equation mathematical whose interpretation resulted in a horizontal asymptote, where the Cost variable becomes smaller and smaller, but will never be exactly zero, no matter how large the variable cable length.

This result, according to Field, Miles and Field (2012), used mathematical criteria to assemble the model. Therefore, it denotes that for large lengths, the cost may decrease, but the rate of reduction is very small and according to the same study the use of theoretical criteria is more recommended to create models than using mathematical criteria.

5 CONCLUSION

The present study sought to determine the contribution of offshore wind energy to the matrix energy of the Northeast of Brazil, integrating a utility maximization model for the expansion of the generation of this source aiming at the distribution preferences of development sustainable. Based on the proposed objectives, it is verified that it was possible to describe the relevance of wind energy in the Northeast from the characterization of the historical evolution of energy wind power, as well as investment at national and global levels and point out perspectives. Furthermore, data compilation was carried out in order to identify the productive capacity of the region, by through the mapping of characteristics of existing wind farms and relevant variables and, finally, determine an initial cost model for offshore energy parks in the Northeast from the application of the Multiple Linear Regression Model.

The results obtained showed that investment in offshore in Brazil has as main characteristics:

a) requires significant investments in technology and research to increase energy generation by this matrix, since, through this path, the country can further reduce more dependence on fossil fuels and adverse climatic conditions, which negatively impact the hydroelectric source of energy production;
b) the expansion of this matrix will help reduce GHG Emissions from Energy Generation, which, in the case of self-production, is compromising the goals of GHG reduction and the fight against climate change, especially in the industrial sector, significant contributor to greenhouse gas (GHG) emissions associated with electricity generation. This occurs because many industries operate their own generating units, generally using fossil fuels, such as fuel oil, natural gas and coal, the burning of which results in the direct release of CO_2 and other GHGs. Consequently, total emissions from the energy sector increase, which results in a higher emission factor, compared to the national average;
c) investment in this renewable source will result in growth of the national industry, as well as the trade of this energy, stimulating the economy;
d) challenges and limitations in infrastructure and insufficient and even restricted supply chain that require a more significant look by government authorities in order to promote the reduction of setbacks caused by increased costs and rates of interest;
e) the finding of the advancement of regulation, as is the case of Decree No. 10,946, sanctioned in January 2022, which solved the problem of overlapping parks offshore. Which is also the case of the most recent Law No. 15,097 that restructured and clearly organized the allocation of maritime areas via competitive bidding, which in turn, ensured transparency and predictability, essential for investment in the

generation of this energy matrix. The aforementioned recent law also requires studies of environmental impact and public consultation with those involved, aligning incentives with the matrix energy and advancing in international agreements and other regulations of a environmental nature, such as issues generated by conflicts caused by noise and interference in the marine ecosystem;

f) the growth of the country's installed energy capacity was noticeable, which was explained by the investment in wind energy generation, expressed in the results graphs presented (more specifically by Graph 3). This was also verified by the acceleration of the growth of onshore energy generation expressed in the result of the inferential statistical analysis, as described in Table 4 and Graph 4.

g) it is evident that the incentive for technical development and feasibility studies economic aspects of characteristic items of each wind farm, both in the legal and in the political sphere, allows for a greater range of growth and interest on the part of multinationals, with a view to investment and export of technology. It's about expertise produced by renewable energy sources, as occurs in France, whose offshore energy matrix is being the subject of application of funds, since 2022. This scenario configures an increasing trend that is being driven by the economic development. In turn, there is greater consumption of electricity and of the energy transition;

h) the model validated for the offshore farms in the Northeast region, resulting from simulations of scenarios with variations of specific parameters (such as distance from the coast, depth, cable length), allowed the identification of the variables with the greatest impact on the total cost of the parks studied in this work, expressed by the values of the coefficients of the regression equation pronounced in the developed models.

i) The study applied statistical models that express the quality of the results exposed and, therefore, can be used to estimate the costs of new projects based on the initial characteristics of each offshore park. The description of a cost model from from the application of Multiple Linear Regression (MLR) in variables directly related to investments in offshore wind energy, initially considered the CAPEX generation cost since it is the first cost portion of the life cycle of a offshore wind farm and, therefore, the specific variables of this were raised stage, namely: park power, distance to the coast, cable length of energy export, park area and depth of the wind turbine structures.

j) From the analysis of Table 16 obtained by the MLR, the park power variable demonstrated statistical inconsistency, observed in the results of Model 1, in consequence of the direct influence of this variable on the calculation of CAPEX. This fact revealed the need to reformulate the aforementioned model, in an attempt to understand and represent the factors that impact this cost, in order to better estimate the factors that most influence this stage of the project. The better understanding of which variables showed more influence on this cost was evidenced by the existence of heteroscedasticity and non-normality of the residuals of the studied model, suggesting that the variation in cost was not yet fully explained.

k) the result of the rejection of the homoscedasticity hypothesis, obtained through the test of Breusch-Pagan announced that the model's errors were not distributed uniformly, making predictions less reliable. And on the other hand, the absence of autocorrelation of the residuals, as demonstrated by the Durbin-Watson test, showed that the model maintained a relatively coherent internal structure.

Despite the existing limitations, this model helps in the planning and management of investments in the energy sector. Cost forecasting can allow companies to make more informed strategic decisions, reducing financial risks and optimizing allocations of resources. In addition, governments and regulatory agencies can use these estimates to structure public policies that encourage renewable energy projects, ensuring that investments are directed efficiently and sustainably.

The difficulties faced by the model affect its practical applicability since the variation in costs may be associated with factors not considered, such as fluctuations in the raw materials market, exchange rate variations and regulatory changes. The lack of data on tax incentives, government subsidies and operating costs may compromise the accuracy of forecasts. These aspects demonstrate that, for the model to be effectively used in strategic decision-making, it needs to be constantly improved and updated with new information.

Although the current model has limitations, it represents an advance in understanding the determinants of CAPEX generation cost. With the development of more approaches robust and the incorporation of new explanatory factors, the tool can become an ally important for companies, investors and public policy makers in planning energy. Thus, the study not only identifies challenges in statistical modeling, but also points out ways to make forecasts more reliable and useful in practice.

Another fact to be considered in this study is that this transition to a more electrified and sustainable system brings challenges to energy security, mainly due to concentration of the production of essential minerals in a few countries, such as China, and other factors involving national public policies, and therefore policies must be constantly adjusted to ensure global energy security.

In addition, there is a large financial deficit to meet the goal of tripling renewable energies. This requires investments in infrastructure modernization, development of regulatory frameworks, and workforce qualification. Subsidy reform will also be fundamental to enabling investments, especially in developing countries (GWR, 2024).

Furthermore, as observed in the last ten years, the share of fossil fuels in the global energy mix has shown a reduced decrease. Given the growth in population and economy, demand has grown in arithmetic progression. Even with studies and research to raise the possibilities of reducing GHG emissions, the awareness of the challenges encountered to balance sustainability and development, with energy security and the technological requirements necessary for first world countries, makes it necessary to carry out financial planning that enables changes and investments for a future with the guarantee of sufficient natural resources for the next generations.

Isolated Systems maintained high emissions throughout the period due to dependence on fossil fuels, with little progress in replacing them with renewable sources. Self-production, on the other hand, showed a progressive reduction in emissions, driven by the growth in the use of biomass, solar, and wind power. During water crises (2014-2015 and 2020-2021), emissions increased in both sectors due to the activation of fossil thermal power plants. Natural gas was a key fuel in the transition, reducing the carbon footprint of self-production compared to coal and diesel.

It should also be noted that, in a scenario in which the demand for coal in the markets emerging and developing economies is responsible for about 70% of the increase in emissions, the diversification of the energy mix effectively contributes to counterbalancing the use of these non-renewable sources, found in industrial development, in the markets emerging and in developing economies.

This panorama reinforces the need to accelerate the transition to renewable energies, especially in Isolated Systems, to reduce the environmental impact of electricity generation in Brazil. Although the electricity sector is the largest emitting energy sector currently, many actions are still underway to reduce these emissions, driven by commitments national and international, in the effort to decarbonize electricity and achieve the abandonment of fossil fuels, according to net-zero emission reduction targets by 2050, defined at COP28. According to the IEA (2024c), wind energy is one of the cheapest sources of electricity in most markets, in addition to expanding and modernizing the grids of electricity, through more economical and safe energy.

Therefore, based on the results achieved, it is observed that this study contributes to the understanding of the different scenarios associated with the expansion of offshore wind energy in Brazil and the world. In addition, it is possible to point out that future research can deepen the analysis on the feasibility of new financing and management models, as well as on the socioeconomic impacts of the expansion of offshore wind energy in Brazil.

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APPENDICES

ANNEX A – Independent and dependent variables applied to the models

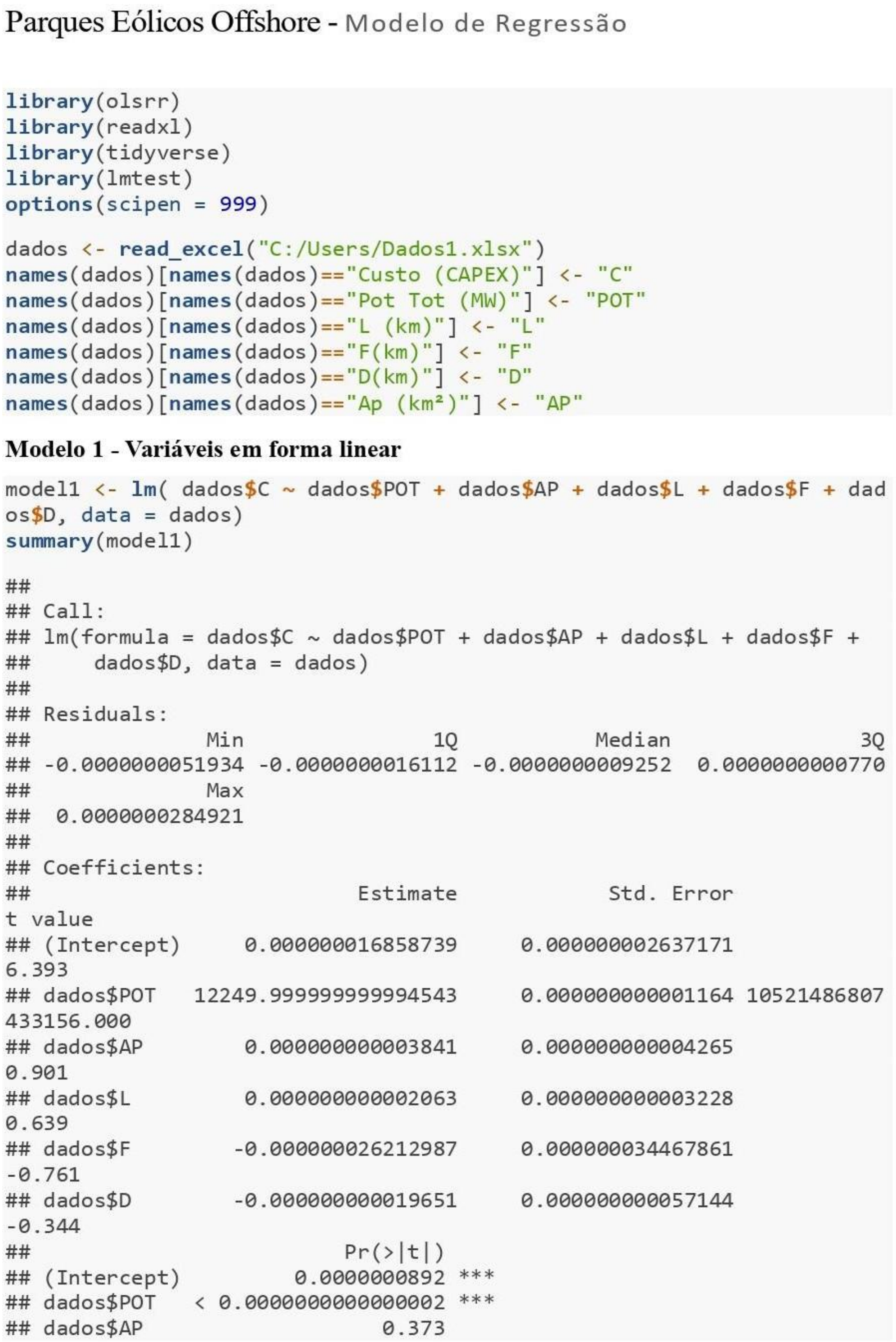
Código	Pot Tot(MW)	***Ap*** (km^2)	***L*** (km)	***F*** (km)	***D*** (km)	***Custo*** **(**CAPEX)
CE-03	3000,00	981347,00	722,00	0,04	24,25	36750000,00
CE-04	1200,00	576854,00	531,00	0,02	12,53	14700000,00
CE-05	1216,00	542772,00	61,00	0,02	26,54	14896000,00
CE-07	3840,00	1580,30	1632,00	0,04	35,80	47040000,00
CE-08	1080,00	244371,00	239,00	0,02	4,62	13230000,00
CE-09	3000,00	540225,00	865,00	0,04	31,06	36750000,00
CE-10	3010,00	682384,00	443,00	0,05	24,16	36872500,00
CE-11	3000,00	779,00	490,00	0,04	10,55	36750000,00
CE-12	2010,00	508,00	81,00	0,03	22,86	24622500,00
CE-13	2010,00	499,00	58,00	0,03	38,30	24622500,00
CE-14	1080,00	244,00	378,00	0,03	22,82	13230000,00
CE-15	2748,00	632,00	387,00	0,04	28,81	33663000,00
CE-16	4320,00	1209,00	1346,00	0,02	7,28	52920000,00
CE-17	4320,00	1276,00	1316,00	0,03	6,52	52920000,00
CE-18	3000,00	601,00	881,00	0,03	21,37	36750000,00
CE-19	3000,00	601,00	780,00	0,02	20,65	36750000,00
CE-20	2955,00	757,00	200,00	0,02	19,86	36198750,00
CE-21	720,00	184,00	113,00	0,02	10,48	8820000,00
CE-22	1500,00	297,00	50,00	0,02	6,46	18375000,00
CE-23	3000,00	576,00	97,00	0,02	5,93	36750000,00
CE-24	1520,00	507,00	214,00	0,02	23,67	18620000,00
CE-25	2394,00	670,00	460,00	0,05	23,18	29326500,00
CE-26	2268,00	634,00	415,00	0,04	17,53	27783000,00
CE-27	2160,00	604,00	419,00	0,05	26,68	26460000,00
CE-28	2016,00	1464,00	629,56	0,06	20,59	24696000,00
MA-01	2640,00	568,00	294,00	0,02	12,28	32340000,00
MA-02	720,00	237,00	227,90	0,04	25,15	8820000,00
MA-03	2808,00	817,00	523,00	0,03	16,87	34398000,00
PI-01	999,00	295,92	218,00	0,02	107,78	12237750,00
PI-02	1395,00	6037,00	409,00	0,02	15,00	17088750,00

ANNEX A – Independent and dependent variables applied to the models (continued)

PI-03	2520,00	430,67	371,00	0,02	15,04	30870000,00
PI-04	2010,00	496,00	72,00	0,02	34,04	24622500,00
PI-05	2955,00	753,00	745,00	0,02	12,87	36198750,00
PI-06	3135,00	303,00	411,00	0,02	22,25	38403750,00
PI-07	2016,00	1131,00	868,00	0,03	14,72	24696000,00
RN-01	624,00	257,91	102,00	0,02	8,50	7644000,00
RN-02	2012,00	534,22	376,00	0,10	11,65	24647000,00
RN-03	1845,00	800,00	830,00	0,03	5,96	22601250,00
RN-04	2484,00	359,82	147,00	0,02	9,58	30429000,00
RN-05	3000,00	864,31	70,00	0,02	10,14	36750000,00
RN-06	1700,00	7779,80	278,00	0,17	11,13	20825000,00
RN-07	1180,00	471,48	93,00	0,11	7,98	14455000,00
RN-08	3010,00	488,32	578,00	0,02	22,60	36872500,00
RN-09	1965,00	493,00	18,00	0,05	16,50	24071250,00
RN-11	1458,00	424,00	299,00	0,04	22,59	17860500,00
RN-12	2106,00	598,00	365,00	0,03	16,62	25798500,00
RN-13	1062,00	345,00	237,00	0,05	16,67	13009500,00
RN-14	3000,00	394,00	458,00	0,04	21,15	36750000,00

Fonte: Ibama (2024)

APPENDIX B – R Program Script Applied to Models



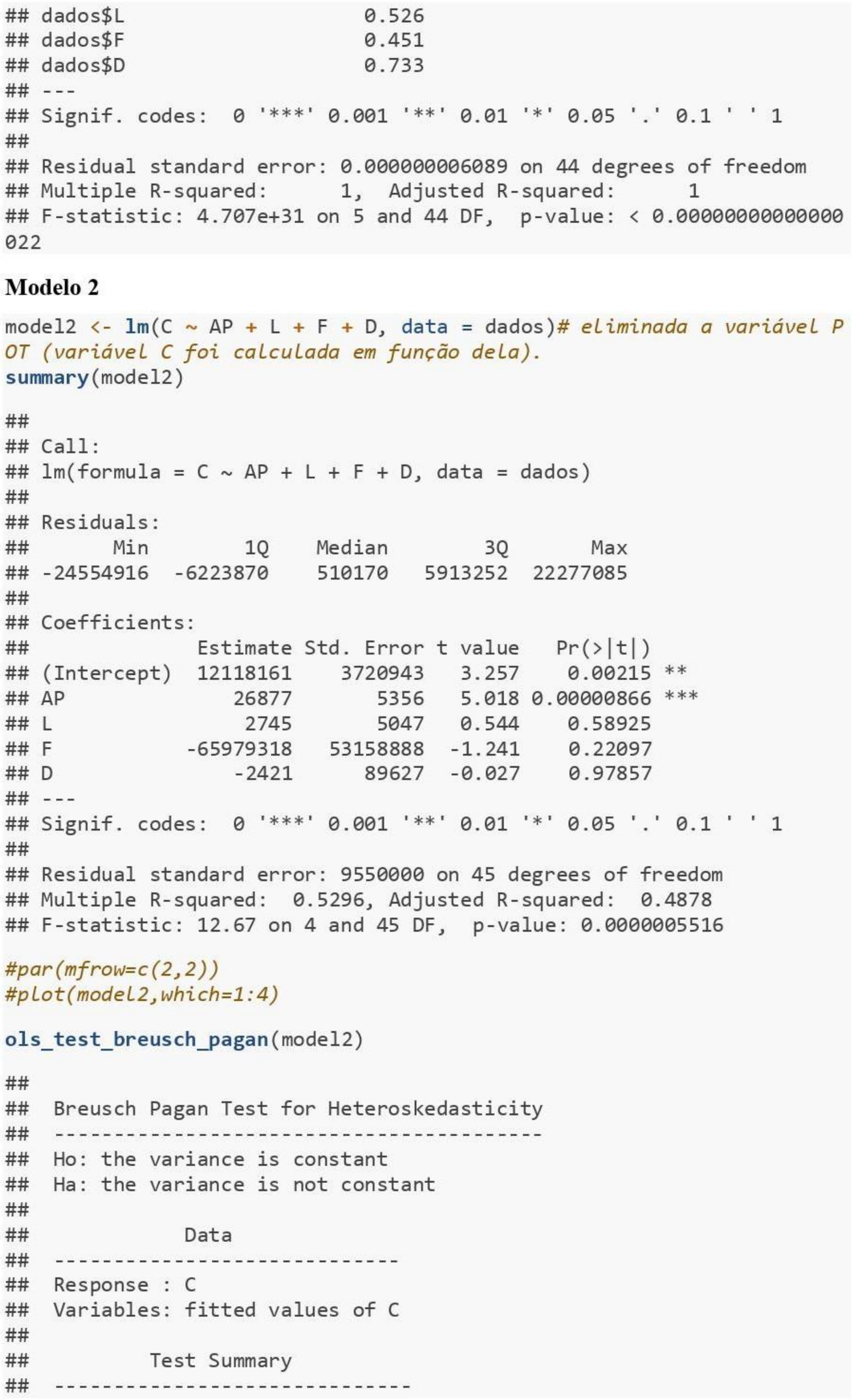
Parques Eólicos Offshore - Modelo de Regressão

```
library(olsrr)
library(readxl)
library(tidyverse)
library(lmtest)
options(scipen = 999)

dados <- read_excel("C:/Users/Dados1.xlsx")
names(dados)[names(dados)=="Custo (CAPEX)"] <- "C"
names(dados)[names(dados)=="Pot Tot (MW)"] <- "POT"
names(dados)[names(dados)=="L (km)"] <- "L"
names(dados)[names(dados)=="F(km)"] <- "F"
names(dados)[names(dados)=="D(km)"] <- "D"
names(dados)[names(dados)=="Ap (km²)"] <- "AP"
```

Modelo 1 - Variáveis em forma linear

```
model1 <- lm( dados$C ~ dados$POT + dados$AP + dados$L + dados$F + dad
os$D, data = dados)
summary(model1)

##
## Call:
## lm(formula = dados$C ~ dados$POT + dados$AP + dados$L + dados$F +
##     dados$D, data = dados)
##
## Residuals:
##               Min                1Q            Median               3Q
## -0.0000000051934 -0.0000000016112 -0.0000000009252  0.0000000000770
##               Max
##  0.0000000284921
##
## Coefficients:
##                           Estimate            Std. Error
t value
## (Intercept)     0.000000016858739     0.000000002637171
6.393
## dados$POT   12249.999999999994543     0.000000000001164 10521486807
433156.000
## dados$AP        0.000000000003841     0.000000000004265
0.901
## dados$L         0.000000000002063     0.000000000003228
0.639
## dados$F        -0.000000026212987     0.000000034467861
-0.761
## dados$D        -0.000000000019651     0.000000000057144
-0.344
##                         Pr(>|t|)
## (Intercept)         0.0000000892 ***
## dados$POT   < 0.0000000000000002 ***
## dados$AP                   0.373
```

APPENDIX B – R Program Script Applied to Models (continued)



```
## dados$L                      0.526
## dados$F                      0.451
## dados$D                      0.733
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 0.000000006089 on 44 degrees of freedom
## Multiple R-squared:      1,  Adjusted R-squared:      1
## F-statistic: 4.707e+31 on 5 and 44 DF,  p-value: < 0.00000000000000
022
```

Modelo 2

```
model2 <- lm(C ~ AP + L + F + D, data = dados)# eliminada a variável P
OT (variável C foi calculada em função dela).
summary(model2)
```

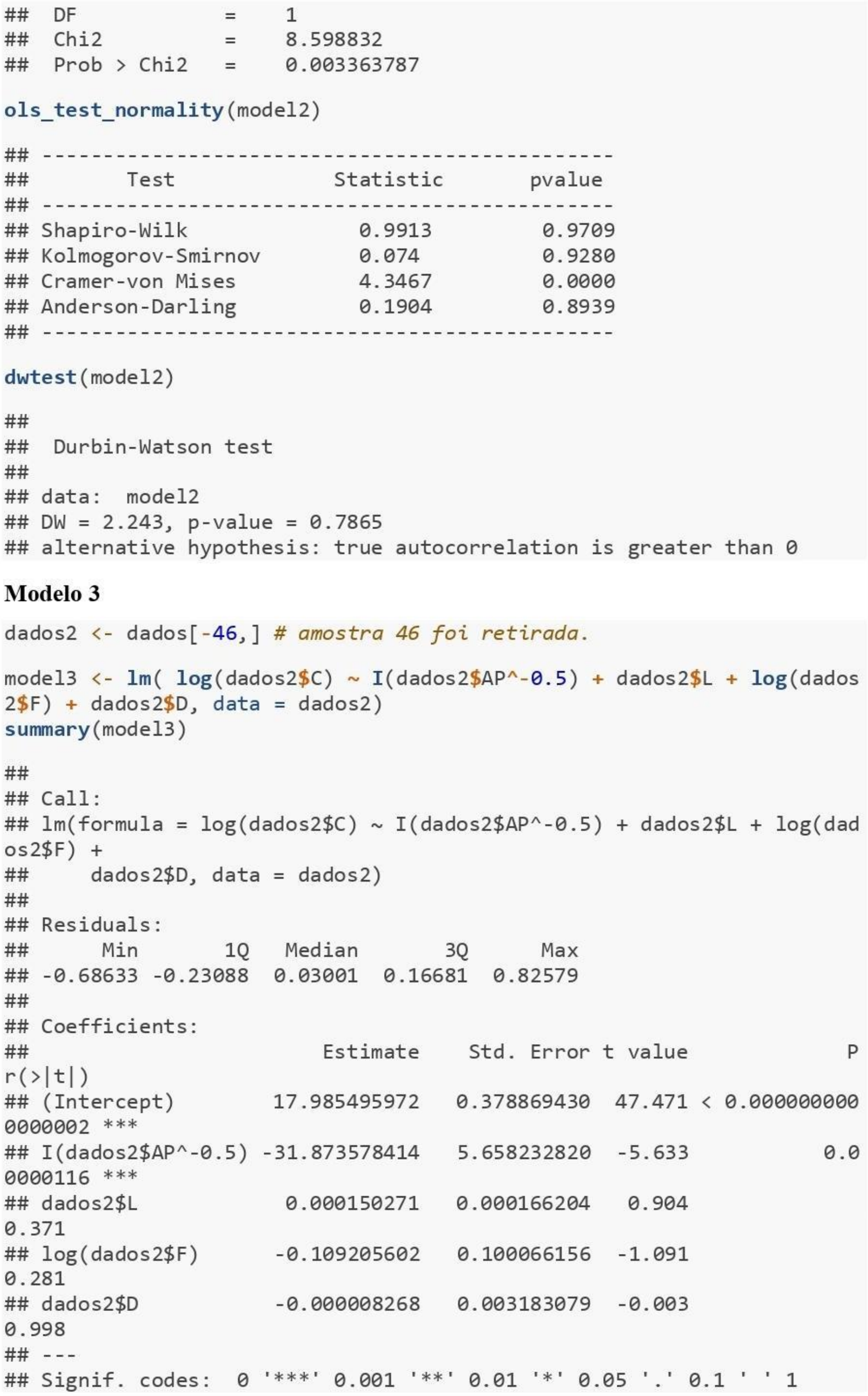
```
##
## Call:
## lm(formula = C ~ AP + L + F + D, data = dados)
##
## Residuals:
##       Min        1Q    Median        3Q       Max
## -24554916  -6223870    510170   5913252  22277085
##
## Coefficients:
##                Estimate Std. Error t value   Pr(>|t|)
## (Intercept)  12118161    3720943   3.257    0.00215 **
## AP              26877       5356   5.018 0.00000866 ***
## L                2745       5047   0.544    0.58925
## F           -65979318   53158888  -1.241    0.22097
## D               -2421      89627  -0.027    0.97857
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 9550000 on 45 degrees of freedom
## Multiple R-squared:  0.5296, Adjusted R-squared:  0.4878
## F-statistic: 12.67 on 4 and 45 DF,  p-value: 0.0000005516
```

```
#par(mfrow=c(2,2))
#plot(model2,which=1:4)
```

```
ols_test_breusch_pagan(model2)
```

```
##
##  Breusch Pagan Test for Heteroskedasticity
##  -----------------------------------------
##  Ho: the variance is constant
##  Ha: the variance is not constant
##
##             Data
##  -----------------------------
##  Response : C
##  Variables: fitted values of C
##
##          Test Summary
##  ------------------------------
```

APPENDIX B – R Program Script Applied to Models (continued)



```
##  DF              =    1
##  Chi2            =    8.598832
##  Prob > Chi2     =    0.003363787
```

```
ols_test_normality(model2)
```

```
## -----------------------------------------------
##        Test             Statistic       pvalue
## -----------------------------------------------
## Shapiro-Wilk              0.9913         0.9709
## Kolmogorov-Smirnov        0.074          0.9280
## Cramer-von Mises          4.3467         0.0000
## Anderson-Darling          0.1904         0.8939
## -----------------------------------------------
```

```
dwtest(model2)
```

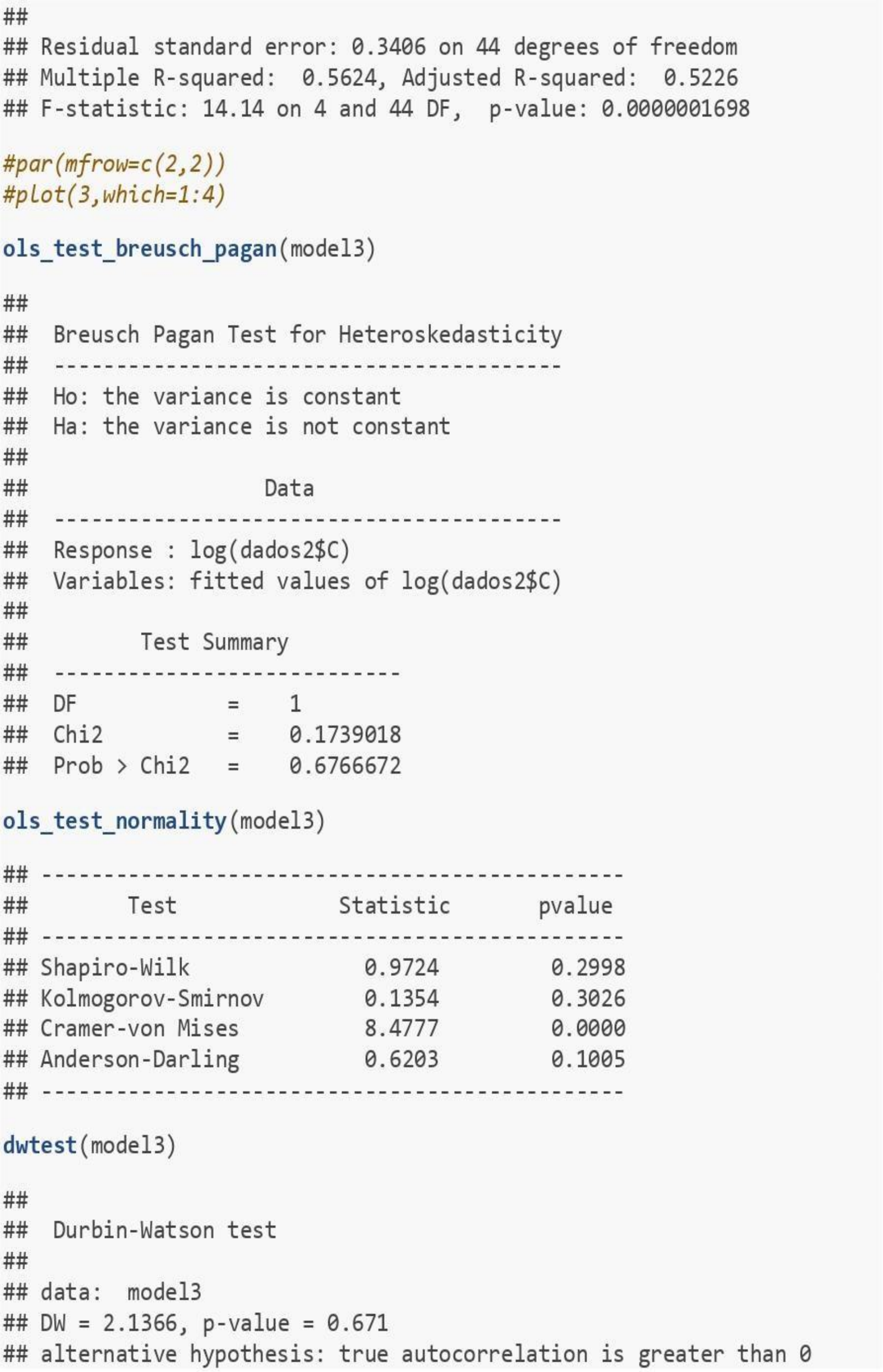
```
##
##  Durbin-Watson test
##
## data:  model2
## DW = 2.243, p-value = 0.7865
## alternative hypothesis: true autocorrelation is greater than 0
```

Modelo 3

```
dados2 <- dados[-46,] # amostra 46 foi retirada.

model3 <- lm( log(dados2$C) ~ I(dados2$AP^-0.5) + dados2$L + log(dados
2$F) + dados2$D, data = dados2)
summary(model3)
```

```
##
## Call:
## lm(formula = log(dados2$C) ~ I(dados2$AP^-0.5) + dados2$L + log(dad
os2$F) +
##     dados2$D, data = dados2)
##
## Residuals:
##      Min       1Q   Median       3Q      Max
## -0.68633 -0.23088  0.03001  0.16681  0.82579
##
## Coefficients:
##                        Estimate    Std. Error t value             P
r(>|t|)
## (Intercept)        17.985495972   0.378869430  47.471 < 0.000000000
0000002 ***
## I(dados2$AP^-0.5) -31.873578414   5.658232820  -5.633           0.0
0000116 ***
## dados2$L            0.000150271   0.000166204   0.904
0.371
## log(dados2$F)      -0.109205602   0.100066156  -1.091
0.281
## dados2$D           -0.000008268   0.003183079  -0.003
0.998
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

APPENDIX B – R Program Script Applied to Models (continued)



```
##
## Residual standard error: 0.3406 on 44 degrees of freedom
## Multiple R-squared:  0.5624, Adjusted R-squared:  0.5226
## F-statistic: 14.14 on 4 and 44 DF,  p-value: 0.0000001698

#par(mfrow=c(2,2))
#plot(3,which=1:4)

ols_test_breusch_pagan(model3)

##
##  Breusch Pagan Test for Heteroskedasticity
##  -----------------------------------------
##  Ho: the variance is constant
##  Ha: the variance is not constant
##
##                 Data
##  -----------------------------------------
##  Response : log(dados2$C)
##  Variables: fitted values of log(dados2$C)
##
##         Test Summary
##  ---------------------------
##  DF            =    1
##  Chi2          =    0.1739018
##  Prob > Chi2   =    0.6766672

ols_test_normality(model3)

## -----------------------------------------------
##        Test             Statistic       pvalue
## -----------------------------------------------
## Shapiro-Wilk              0.9724         0.2998
## Kolmogorov-Smirnov        0.1354         0.3026
## Cramer-von Mises          8.4777         0.0000
## Anderson-Darling          0.6203         0.1005
## -----------------------------------------------

dwtest(model3)

##
##  Durbin-Watson test
##
## data:  model3
## DW = 2.1366, p-value = 0.671
## alternative hypothesis: true autocorrelation is greater than 0
```