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TECHNOLOGICAL ROUTES FOR THE WIND POWER GENERATION IN BRAZIL: A FEASIBILITY STUDY FOR THE STATE OF CEARÁ

Rotas tecnológicas para a geração de energia eólica no Brasil: estudo de viabilidade para o estado do Ceará

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ABSTRACT

Most of the electricity generated in Brazil still comes from hydroelectric plants. In 2021, the country reached a critical hydrological scenario due to low capacities in the reservoirs. Although the installed wind power capacity in Brazil has expanded considerably in recent years, wind generation in the country is limited to the onshore type. This study aims to evaluate the feasibility of a new wind farm to be installed in Brazil, comparing several possible conditions and technologies, for installing a wind farm on a predetermined location in the northeast region of the country, the most promising region for wind farms. Based on the literature review, different technology routes that characterize wind farms around the world were identified and, through expert evaluation, the best technology route in terms of cost-effectiveness was defined. The results show that, under current conditions, the onshore route with higher unit power of the wind turbine and tubular tower proved to be the preferred one. However, it was shown that in the medium term, offshore wind energy shall become a reality in the country, as long as favorable regulations and licensing models, political and economic stability, and long-term public policies in terms of incentives and subsidies to attract investments for this type of energy generation are present.

Keywords: Renewable Energy; Wind Energy; Public Policy; Feasibility Study; Brazil.

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ROTAS TECNOLÓGICAS PARA A GERAÇÃO DE ENERGIA EÓLICA NO BRASIL: ESTUDO DE VIABILIDADE PARA O ESTADO DO CEARÁ TECHNOLOGICAL

Technological routes for the wind power generation in Brazil: a feasibility study for the state of Ceará

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RESUMO

A maior parte da energia elétrica gerada no Brasil ainda vem de usinas hidrelétricas. Em 2021, o país atingiu um cenário hidrológico crítico devido à baixa capacidade nos reservatórios. Embora a capacidade instalada de energia eólica no Brasil tenha se expandido consideravelmente nos últimos anos, a geração eólica no país está limitada ao modelo onshore. Este estudo tem como objetivo avaliar a viabilidade de um novo parque eólico a ser instalado no Brasil, comparando diversas condições e tecnologias possíveis para a instalação de um parque eólico em local pré-determinado na região nordeste do país, a região mais promissora. Com base na revisão da literatura, foram identificados diferentes modelos de rotas tecnológicas que caracterizam parques eólicos ao redor do mundo e, por meio de avaliação de especialistas, foi definida a melhor rota tecnológica em termos de custo-efetividade. Os resultados mostram que, nas condições atuais, a rota onshore com maior potência unitária da turbina eólica e de torre tubular provou ser a preferida. No entanto, mostrou-se que, a médio prazo, a energia eólica offshore se tornará realidade no país, desde que existam regulamentos e modelos de licenciamento favoráveis, estabilidade política e econômica e políticas públicas de longo prazo em termos de incentivos e subsídios para atrair investimentos para esse tipo de geração de energia

Palavras-chave: Energia Renovável; Energia Eólica; Políticas Públicas; Estudo de Viabilidade; Brasil

INTRODUCTION

The world's electricity matrix is made up of 74.1% of energy from non-renewable sources and 25.9% from renewable sources (IEA, 2020). On the other hand, the Brazilian electricity matrix is made up of 16.79% non-renewable and 83.21% renewable sources (ANEEL, 2021). Thus, it can be inferred that the Brazilian electric matrix is more sustainable than the world average. Most of the electricity used in Brazil still comes from hydroelectric plants. In 2020, the hydraulic supply was 421 TWh, representing 65.2% of the total national electricity supply (EPE, 2021).

As described by MME (2021), the country is going through a critical hydrological scenario in 2021, with the lowest flows since 1930, when data recording began. Since September 2020, the Electricity Sector Monitoring Committee - CMSE has held ordinary monthly meetings and weekly technical meetings with the aim of monitoring electricity supply conditions and coordinating actions among the main agencies that act in the planning, operation, regulation, and commercialization of energy. Hunt et al (2018) point out that Brazil has experienced several energy crises in its history.

It is evident the current governmental concern with a new energy crisis in a scenario of potential economic growth and low affluent natural energies. The federal government, through Provisional Measure no. 1.055/2021 (Brasil, 2021), instituted the Chamber of Exceptional Rules for Hydropower Management with the objective of establishing emergency measures for the optimization of the use of hydroelectric resources and for confronting the current situation of water shortage, in order to guarantee the continuity and security of the country's power supply. In addition, a report was created on the hydric situation and its impact on the generation of electricity (MME, 2021). In this scenario, wind power generation gains importance and becomes timely (Canal Energia, 2020; Climainfo, 2021; O Globo, 2021).

The wind power capacity installed in Brazil has expanded considerably in recent years. According to ABEEOLICA (2021), this capacity jumped from 928 MW in 2010 to 17,750 MW in 2020, which represents an average growth rate of 34.33% per year. ABEEOLICA (2021) also indicates that 86.7% of all wind power generated in Brazil in 2020 came from the Northeast region, with the states of Bahia, Rio Grande do Norte, Ceará and Piauí standing out.

In April 2021, Ceará had 94 onshore wind farms in operation, with a total power of 2.39 GW and 9 farms with construction not yet started and expected to add 0.24 GW of power to the system (ANEEL, 2021). The energy atlas of the State of Ceará, released in 2019 (ADECE, 2019), indicates that the onshore wind energy potential in the state is estimated at 42 GW for winds greater than 7.0 m/s at 100 m height, a value that is much higher than the installed capacity until April 2021 (2.39 GW). For the same wind and height conditions, the offshore installable capacity, non-existent in the state so far, is 117 GW. Thus, it can be deduced that the wind industry is in an initial growth phase in the state of Ceará and with a lot of potential for expansion in the coming years. Because of the possibility of a new energy crisis in 2021 and the need to diversify the country's energy sources in order to make it less susceptible to crises in the electricity sector, the prospect is that public policies and investments will be made to increase the national installed capacity from alternative sources of energy. By virtue of being a renewable and abundant source, the quality of the winds in the Northeast, the level of development of the national wind industry, and the accumulated expertise of local labor, wind energy should continue to expand considerably in the coming years in the region, especially in the state of Ceará (ADECE, 2019). Based on this discussion, the state of Ceará was chosen as recipient of the hypothetic wind farm that is the focus of this study. It can be argued that the state is an adequate representative of a location that has good potential for a wind farm in the country.

The objective of this work is to evaluate the feasibility of a wind farm to be installed in Ceará, Brazil. Different technological routes that characterize wind farms around the world will be verified, in order to identify which is the best option, especially in terms of cost-effectiveness for the enterprise. For these purposes, a comprehensive analysis will be conducted that will include, in addition to a qualitative-quantitative analysis, an additional qualitative assessment by experts working on large engineering projects in Brazil.

This paper is organized into five sections: besides this Introduction, section 2 shows the Literature Review; section 3 describes the Methodology; section 4 discusses the Results and Discussion, and section 5 presents the Conclusion.

1 LITERATURE REVIEW

GWEC (2021) indicates that the installed onshore wind capacity in the world increased more than three and a half times between 2010 and 2020, from 195 GW to 707 GW. All wind power generated in Brazil to date comes from onshore wind farms. In 2020, Brazil had a total capacity of 17.75 GW from this source, occupying the seventh position in the world ranking of accumulated wind capacity (ABEEOLICA, 2021).

According to Musial (2007), onshore wind energy has undergone a significant reduction in cost in recent decades, even becoming competitive with fossil fuels and nuclear energy in many areas of the United States. Technology has been improving rapidly and the cost of wind power generation in onshore facilities has been decreasing considerably (Laudari et al., 2015). As for offshore wind energy, Musial (2007) emphasizes that significant R&D is still required to reduce capital and operating costs and increase turbine performance before significant levels of market penetration are achieved.

The offshore wind capacity installed in the world in 2020 was 35.29 GW, with 70.37% coming from wind farms installed in Europe (GWEC, 2021). Brazil has an offshore installable capacity of 697 GW (EPE, 2020). The Northeast is the region of Brazil with the highest offshore wind potential with wind speeds above 7m/s, at 100 meters height and in places with depth up to 50 meters: 356 GW (51,08%), followed by the North with 197 GW (28,26%), Southeast 97 GW (13,92%) and South 47 GW (6,74%). Considering the size of the ocean, the use of offshore wind energy can be extended to several areas that are still poorly explored and may offer greater growth potential compared to other renewable energy sources (Junqueira et al., 2020).

In the case of Ceará, the offshore potential is benefited by the reduced depth of the territorial sea and by the high wind speeds along the coast. These characteristics place Ceará in a prominent position in the world scenario (ADECE, 2019). Junqueira et al. (2020) point out that in offshore wind farms, the cost of wind turbines, towers and foundations is much higher than onshore developments, which can be explained mainly due to the high costs of maritime operations.

For onshore wind farms, the main foundation types used are direct or indirect foundation. The selection will depend on the characteristics of the soil where the wind farm will be installed. As for offshore installations, the main criteria for the selection of a foundation type include water depth, marine soil conditions, turbine characteristics, rotor and nacelle masses, rotor speed, experience and capacity of the supply chain (both in manufacturing and installation of the foundations) (IRENA, 2016). For this study, the types of foundation evaluated are: direct or indirect (onshore) and single-stack, jacket or gravity (offshore) (EPE, 2020; Musial, 2007).

Most of the wind turbines used in wind farms around the world are of the horizontal axis type. However, studies indicate that vertical axis wind turbines can prove advantageous over horizontal axis wind turbines, and some characteristics of the offshore sector offer opportunities for this type of turbine (Ashwill et al., 2012). The costs of component removals in offshore farms is much higher than in onshore farms. In vertical axis turbines, the main components are located close to the water level, avoiding the use of large cranes and activities at higher levels, thus reducing the costs of installation, maintenance and services, as well as increasing safety (EPE, 2020).

Wind towers can be of the conical or lattice type and built from different materials. The conical towers can be made of rolled steel or prestressed concrete, and lattice towers use galvanized steel. In the hybrid (conical) towers, the bottom part of the tower (about 60 meters) is built in concrete and the top part is made of steel. The choice of the tower type/material depends on factors such as cost, height of the wind turbine, ease of transport, assembly and maintenance (Custódio et al., 2013).

The lifetime of a wind farm, for the purpose of a feasibility study, is 20 years (Effiom et al., 2016; Samu et al., 2019). Tom Gray's rule of thumb considers that 60 acres of area per megawatt is required for onshore wind farms (AWEO, 2021).

From the technical point of view, Bailey et al (1997) demonstrated that for wind speeds higher than class 3 (wind speed greater than 7 m/s) and height above 50 meters, the environmental conditions are considered favorable for most wind turbine applications. As described by Li et al. (2012), wind speed tends to increase at higher heights as a consequence of decreasing obstacles (buildings and vegetation). Furthermore, as the efficiency and performance of new wind turbines are continuously increasing, the choice of a site with good wind quality becomes essential (Walters & Walsh, 2011).

The availability and quality of the distribution grid, as well as the connection to the National Integrated System (SIN) is a technical point that needs to be considered during the feasibility study of a wind farm. Venkatesh (2002) showed that the poor quality of the distribution network affects the performance of the wind turbine, creating power quality problems. Due to this, the operational efficiency of the wind farm is reduced and results in poor power quality in the grid, increasing losses for consumers. Other studies have highlighted that interconnection problems with the national electricity system have generated significant delays for the start of operation of wind farms in Brazil (Köberle et al., 2018; Martins & Pereira, 2011).

Brazil, through incentives from BNDES (National Development Bank), has been developing a competitive national wind industry. In Ceará, for example, there are two wind blade factories (AERIS and WOBBEN), two wind turbine factories (VESTAS and WOBBEN), two concrete tower factories (CTZ Eolic Tower and CASSOL) and one steel tower factory (Nordeste Torres do Brasil) that supply products and services to the national and international markets (ABDI, 2017).

From an economic perspective, to maximize the return to investors, the location of the wind farm should consider a region that minimizes conflicts of interest with other stakeholders (Brannstrom et al., 2017; Viana et al., 2016) and that allows optimizing the costs described by Effiom et al (2016): CAPEX (Pre-development & Consent, Procurement & Acquisition, Installation & Commissioning), OPEX (Operation & Maintenance) and Decommissioning & Final Disposal.

The global weighted average installed cost of onshore wind projects fell by 74% between 1983 and 2020, from US$5,241/kW to US$1,355/kW, based on data from the IRENA Renewable Cost Database. In the last decade, the reduction was 31% between 2010 and 2020, from US$ 1,975/kW to US$ 1,355/kW (IRENA, 2020). On the other hand, the global weighted average installed cost of offshore installed wind projects increased from around US$ 2,592/kW (kilowatts) in 2000 to over US$ 5,500/kW in 2008 and jumped to values around US$ 5,000/kW for the period 2008 to 2015 as projects moved away from the coast to waters further offshore. The overall weighted average installed cost began to decline only after 2015, falling relatively quickly to US$ 3,185/kW in 2020 (IRENA, 2020). At this point, it is worth noting that technological development has allowed wind energy to carry out more robust projects, in challenging conditions and which are becoming increasingly competitive in relation to other sources of energy generation.

Kaldellis & Gavras (2000), when conducting an economic feasibility study of wind farms in Greece, concluded that three categories can impact the payback of a wind farm. In the first category, the increase in capacity and electricity price reduce the payback period, given that a moderate increase in their value leads to a significant decrease in payback. In the second category, cost of the initial investment, the price of the necessary equipment and the cost of operation and maintenance of the facility influence the economic viability of the wind farm in a negative way, since a moderate increase in these parameters imposes a notable increase in the payback period of the project. Finally, the third category includes the inflation rate and the rated power of wind turbines. It was concluded that these parameters slightly influence the payback.

The application of small and medium wind turbines as an alternative and reliable source of electricity in developing countries has been the focus of different authors, mainly to serve rural areas that do not have access to the transmission grid (Ayodele et al., 2014; Bortolini et al., 2014). These authors suggest that government financial incentives be offered to consumers to increase demand and drive technology development (capital subsidies). Li et al. (2012) concluded that government support proved to be extremely important in the deployment of small wind turbines for domestic use in Ireland.

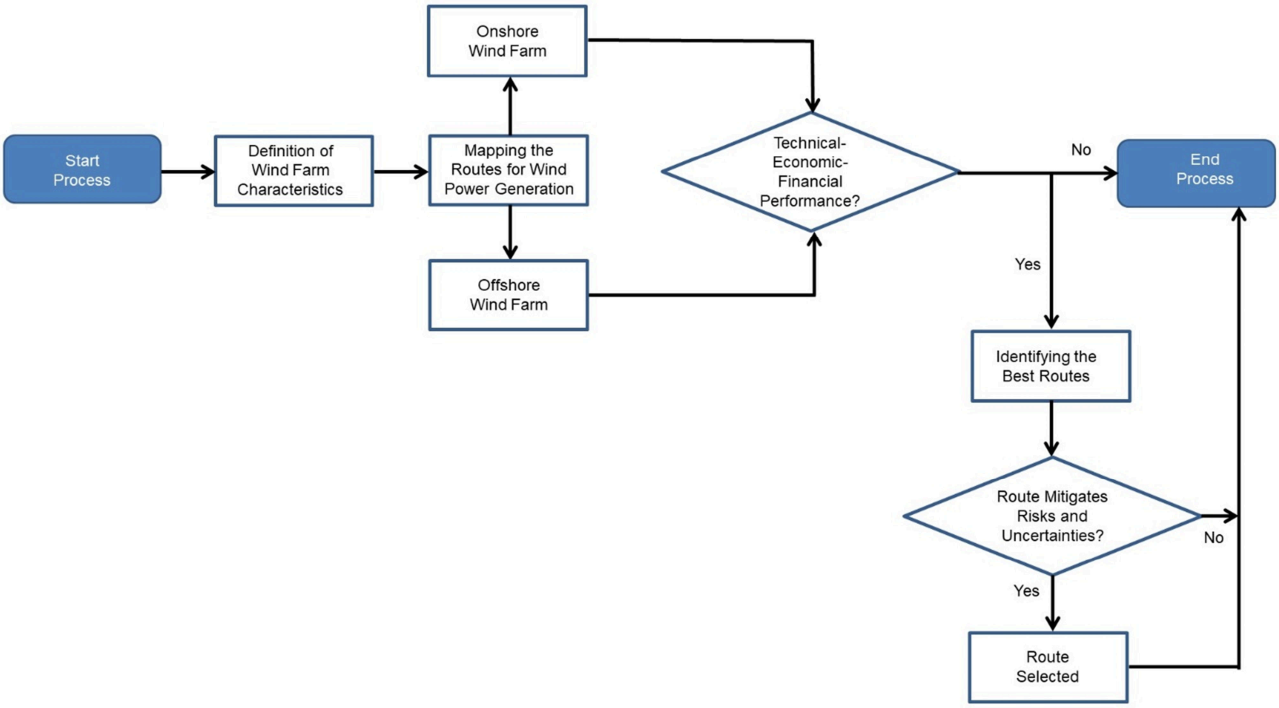
Although offshore wind energy is a promising technology to meet the long term targets established for renewable energy deployment (Brown et al., 2015), the Levelized Cost of Energy is still high when compared to other sources of energy supply and financial support mechanisms are required to make it competitive (Ariola Mbistrova & Aloys Nghiem, 2017; O'Keeffe & Haggett, 2012). To reduce the risks and uncertainties of this type of venture, Junqueira et al. (2020) suggest the creation of an industrial cluster that allows cooperation among companies; the transfer of technology and knowledge between the aggregated sectors and social support, considering that the creation of this type of project needs acceptance by society to move forward.

2 METHODOLOGY

The processes and methods used for this study are described in this section. Activities include literature review, expert interviews and qualitative and quantitative analysis of the results obtained.

In order to define the characteristics of a wind farm to be installed in the State of Ceará, the methodological path shown in Figure 1 will be used.

Figure 1 - Methodological pathway



Source: The Authors.

Data were collected through semi-structured interviews, using a questionnaire as a guide, and the answers were analyzed and qualitatively categorized according to content. Data analysis was initially performed by the graduate student and, subsequently, the data were reassessed by two PhD-level researchers, in an attempt to reduce biases or distortions arising from the interviewer's experience and subjective interpretation. No distortions were identified.

Based on the data obtained from the Wind Atlas of Ceará (ADECE, 2019), which is the state chosen for this feasibility study for reasons already mentioned, the characteristics of the wind farm were defined: location, distance from the coast, depth, height of the wind turbines, wind speed and other relevant aspects.

A mapping of eight possible technological routes for the implementation of the wind farm was made, being four onshore and four offshore routes. In addition, different types of towers, turbines and foundations were suggested, according to models that are already applied or are under construction for this type of enterprise in Brazil and worldwide, as discussed in the literature review. These eight possible routes aim to encompass possible solutions that are potentially more viable, in terms of power of the wind turbines, number of wind turbines in the wind farm, type of tower used and type of foundation.

The technical-economic-financial performance was assessed using the weighted factor scoring method (Lourenço et al., 2020; Rocha & Figueiredo, 2017) to help decide which options were feasible to meet the characteristics of the wind farm under study. This method listed in a table the set of factors amenable to evaluation and the relative weight of each factor that reflects the respective factor's importance in relation to the others. Weights received a score ranging from 1 to 5, whilst scores ranged from 1 to 10.

Ten experts from different backgrounds, who work in large infrastructure projects in Brazil, provided the weights and scores. The interviews were conducted in a face-to-face or online format using the Microsoft Teams platform. The result of this stage of route evaluation was the sum of the products of weights and scores for each factor. The two top-ranked routes moved on to the next stage of the study.

The factors that were evaluated were defined based on the ones mentioned by Ramos Júnior et al. (2022) and are listed in Table 1.

Table 1 - Weighted Score for Evaluation of Technical-Economic-Financial Performance.

Factors	**Weight**	Route1	Route2	Route3	Route4	Route5	Route6	Route7	Route8
Ease of Wind Farm Deployment in Technical Terms									
Ease of Obtaining Technology and Product									
Ease of Implementation in Legal/Regulatory Terms									
Ease and Availability of Maintenance									
Esiness of Connection to the National Interconnected System									
Life expectancy									
Implementation Cost									
Maintenance Cost									
Cost per KW generated									
Speed of return on investment									
Impact on communities									
Impact on environment									
TOTAL (weights x scores)									

Source: The authors.

After the definition of the two highest scoring routes, a new stage of interviews, this time fully qualitative, was conducted with the specialists. Professionals had the opportunity to provide feedback and make comments on the two finalist technological routes, in addition to recommendations and criticism, so as to further enhance the credibility and validity of the decision making process. The objective of this stage was to assess the risks and uncertainties of the two finalist options. The stage was conducted in August 2021 and each interview lasted an average of 1 hour. Through the use of tools available in the Microsoft Teams platform, the interviews were recorded with prior authorization from the interviewees. Based on the evaluation of the experts and the literature review, the best technological route for the construction of a wind farm in the state of Ceará was defined.

3 RESULTS AND DISCUSSION

This section is divided into five subsections: description of the characteristics of the wind farm to be implemented in Brazil; mapping of the pre-defined technological routes, according to a systematic review of the literature; profile of the specialists who evaluated the routes; the results of administering the questionnaire to the specialists; and finally the analysis of the risks and uncertainties, in a qualitative manner, of the two best ranked routes in the questionnaires.

3.1 Wind farm characteristics

The location of the wind farm was chosen considering the availability of good wind speeds, availability of local infrastructure (road and river), and accessibility to the national grid for connection to the National Interconnected System (SIN), among other aspects already mentioned regarding the state of Ceará. The characteristics of the wind farm proposed in this study are detailed in Table 2 below.

Table 2 - Characteristics of the Wind Farm.

Location	Total Power	Wind speed	Wind generator height	Distance from the coast	Depth	Lifetime
Caucaia - Ceará	330 MW	> 7 m/s	100 m	10 – 20 Km	10 – 20 m	20 years

Source: The authors.

Caucaia is a Brazilian municipality in the state of Ceará that integrates the Metropolitan Region of Fortaleza with about 1,227.9 km² and has 44 km of coastline (Prefeitura de Caucaia, 2021). The municipality of Caucaia is bordered by the Atlantic Ocean and located 35 km from the Industrial and Port Complex of Pecém. This location is strategic for the transport of large equipment, devices, accessories and indivisible parts to serve the construction of the Wind Farm using the CE-085 highway or through river transport.

The total wind farm capacity of 330 MW, as shown on table 3, was defined based on the sum of the total wind power capacity that went into operation in 2021 and that is under construction in Ceará and is expected to be completed between 2021 and 2024. The data was extracted from the SIGA System (ANEEL, 2021) on June 19, 2021. Thus, the technological routes of the enterprise, whether onshore or offshore, will be evaluated to meet this total power.

Table 3 - Granted Power of Proposed Ceará Wind Farms.

Wind Farms	Enterprises	Granted capacity (MW)
In operation (2021)	8	205,80
Under construction	6	121,80
TOTAL	**14**	**327,60**

Source: The authors.

The choice of the wind farm location focused on a region with wind speeds above 7m/s and a height of 100 meters for both onshore and offshore wind power generation. For this study, it is assumed that the distance from the coast for the construction of the offshore wind farm is between 10 and 20 kilometers and that the depth of the suitable area at the sea varies between 10 and 20 meters. These data were obtained based on the offshore wind potential of Ceará by distance from the coastline and by depth (ADECE, 2019). The 20 year lifetime of the project was defined based on the studies of Effiom et al. (2016) and Samu et al. (2019).

3.2 Mapping the technological routes for wind power generation

Table 4 describes the characteristics of the eight pre-defined technological routes, according to the criteria already mentioned in the Methodology section, and that were evaluated by the specialists.

Table 4 - Characteristics of the Technological Routes.

Route	Generation type	Power of Wind generators	Number of Wind generators	Tower type	Turbine type	Foundation type
1	*Onshore*	500 MW	660	Lattice	Vertical	Direct
2	*Onshore*	1 MW	330	Concrete	Vertical	Indirect
3	*Onshore*	2 MW	165	Hybrid	Horizontal	Direct
4	*Onshore*	4 MW	83	Tubular Steel	Horizontal	Indirect
5	*Offshore*	8 MW	42	Concrete	Vertical	Gravity
6	*Offshore*	10 MW	33	Lattice	Horizontal	Jacket
7	*Offshore*	12 MW	28	Tubular Steel	Vertical	Monostation
8	*Offshore*	15 MW	22	Tubular Steel	Horizontal	Monostation

Source: The Authors

3.3 Profile of the experts

Table 5 describes the characteristics of the experts who were consulted. The interviews were conducted with a multidisciplinary group of professionals, aiming to offer a multiplicity of points of view, i.e. enabling an analysis with fewer biases.

Table 5. Information from the Specialists Interviewed.

Interviewee	Type of Interview	Age	Training	Gender	Current Position	Years of Experience in infrastructure projects
1	Virtual	34	Mechanical Engineer	Male	Assembly Coordinator	10
2	Face-to-face	37	Telecommunications Engineer	Male	Safety, Health and Environment Coordinator (SHE)	11
3	Face-to-face	24	Naval Engineer	Male	Port Analyst	4
4	Virtual	37	Chemical Engineer	Male	Regulatory Analyst	10
5	Virtual	32	Mechanical Engineer	Male	Maintenance Supervisor	14
6	Virtual	27	Civil Engineer	Female	Specialist Civil Engineer	5
7	Virtual	34	Engenheiro Eletricista	Male	Power System Engineer	9
8	Virtual	49	Civil Engineer	Male	Site Manager	16
9	Face-to-face	41	Electrical Engineer	Male	Electrical Engineer Specialist	16
10	Face-to-face	35	Electrical Engineer	Male	Electrical Engineer Specialist	10

Source: The Authors.

3.4 Technical-economic performance

The first stage of interviews (questionnaire and qualitative assessment of weighted factor scores) was conducted between June and July 2021 and lasted between 45 minutes and 1 hour each. Most interviews were conducted virtually (a total of 6) and the remainder were conducted face-to-face (a total of 4). Table 6 shows the results, based on the weighted factor method.

Table 6 - Result of the Factor-Weighted Method.

	Route 1	Route2	Route 3	Route 4	Route 5	Route 6	Route 7	Route 8
Interviewee	**(Weight x Score)**							
1	257	253	240	440	224	283	256	343
2	235	289	327	359	338	309	341	323
3	308	350	405	424	358	358	359	366
4	105	153	195	238	277	240	333	316
5	285	272	261	298	227	218	279	267
6	298	395	338	339	204	231	236	253
7	189	209	261	310	266	262	295	322
8	287	365	320	392	254	245	283	296
9	234	268	284	305	250	257	264	280
10	320	340	398	378	290	255	271	274
TOTAL	**2518**	**2894**	**3029**	**3483**	**2688**	**2658**	**2917**	**3040**

Source:The authors.

With a total of 3483 points and 3040 points, route 4 and route 8 (respectively) obtained the highest scores in the experts' evaluations. Route 4 was selected as the best technological route by 6 specialists, whilst route 1 was elected the worst route by 5 respondents. For the two better ranked routes, the risks and uncertainties were evaluated, by means of a qualitative assessment made by the specialists. This qualitative analysis is presented next.

3.5. Assessment of risks and uncertainties

In this section, the results of the interviews are presented.

Interviewee 1 mentioned that:

> *"route 4 should be the selected route, because the onshore technology is already well established in different projects in Brazil and around the world, proving to be technically and economically viable. I also highlight that it is important that the government maintain the agreements previously established when auctions for new wind farms take place. Recently, with the health crisis that affected Brazil and the world, some wind power auctions were cancelled. However, these auctions will provide a total of 249 wind energy blades during a predicted lifetime of 20 years, if no replacement is needed during the operation period due to some unforeseen event (bird strike for example). The question remains as to what environmentally appropriate disposal will be given to these wind blades after the end of their working life."*

Aligned with the interviewee's view, Ramos Júnior & Almeida (2021) identified that the destination of blades used in wind farm turbines is a problem that affects all countries where wind energy generation is present. Landfill disposal or incineration in waste processing plants have been the most common treatment. However, in Brazil there is no law that defines these responsibilities.

On the other hand, Interviewee 2 indicated that:

> *"Alternative 8 (offshore) is decisively the best, due to the smaller amount of generators to be installed and receive maintenance (total of 22) and the smaller area required when compared to route 4, consequently resulting in lower risk of failure and higher probability of fast return on investment. Additionally, the land should be used for a more noble option as agribusiness, animal breeding for beef or residential and industrial areas".*

Using Tom Gray's golden rule criteria (AWEO, 2021), it can be observed that 60 acres of area per megawatt are necessary, resulting in 80.13 Km^2 of necessary area for the installation of the 330 MW proposed in this study. This area is equivalent to the area of the municipality of Eusébio in Ceará (IBGE, 2021). In an area of such huge dimension, there will probably be indigenous and quilombola reserves, permanent protection areas, private areas that owners do not wish to lease, among other aspects that may make the installation unfeasible, or delay the beginning of construction or operation of the wind farm.

Interviewee 3 said that:

> *"despite the visual and noise impacts that the 83 wind turbines will cause to the community, route 4 (onshore) is the best solution among those presented, since route 8 (offshore) requires the use of special equipment: barges, tugboats, special cranes, among others. It is also necessary to consider the time of displacement, attraction and undocking of the ferry to the work site, besides the necessary installation of a wind monitoring system, because - for safety issues in the execution - it is recommended to stop the activities when the wind speed reaches a pre-determined value. Additionally, because it invloves work at sea, it is necessary to have the support of a rescue team and the use of life jackets, which will generate additional costs to the enterprise".*

This point was highlighted by Junqueira et al. (2020) who indicated that the costs of marine operations make the offshore option more expensive than the onshore one.

Interviewee 4 was firm in his decision that:

> *"route 8 (offshore) is the best option, because the sea belongs to a single owner (the Union) which allows greater flexibility regarding the location of the wind farm, according to wind data - on land, it may occur*

> *that the best location is in a mountainous region. In addition, the BR do Mar project, if approved, will allow for a significant reduction in the logistical costs of this type of enterprise."*

BR do Mar is a federal government program that intends to stimulate the use of cabotage, increase the national fleet and balance the Brazilian port matrix (Brasil, 2020). In fact, if it is enacted, it will significantly reduce logistical costs for wind farms.

Interviewee 5 stated that:

> *"Route 4 (onshore) is currently more technically and economically feasible in Brazil because it is easier to implement and maintain onshore farms than offshore farms. In addition, Brazil already has skilled labor, resources and spare parts for this type of enterprise. Offshore projects are exposed to corrosion, higher humidity and saltpeter, which can reduce the life span of wind turbines and increase maintenance costs. Additionally, many companies in the energy industry already use drones in onshore farms, to perform inspections, which have significantly reduced costs, as well as supported professionals in cases of emergency".*

COPEL (2021), IBERDROLA (2021) and TAESA (2021) have projects with drones that offer high technology services for inspection of transmission networks, of components of wind farms and for aiding firefighting activities. It has been demonstrated that it is much cheaper and safer to use this technology for such activitirs, replacing human resources.

Interviewee 6 declared that:

> *"nowadays, due to the ease of implementation, route 4 (onshore) has an advantage over route 8. Besides, there is an inherent difficulty in driving pillars in the sea for the construction of the offshore foundation: Other additional resources are required, such as vessels, special equipment, and other services that may make the project unviable and unfeasible. In addition, it is more difficult to connect the farm to the national interconnected system because part of the cables must be laid in the water and, therefore, special coating is required. Offshore technology needs further development to be considered reliable by investors."*

Interviewee 7, who has experience in offshore oil extraction projects, selected route 8 as the best route and reported that:

> *"both routes are already well established in other countries around the world, and the implementation of route 8 in Brazil presents challenges involving regulation, especially the creation of laws and rules by the federal, state and municipal governments. This can cause a delay in the issuance of environmental, construction and operational licenses. However, the synergy with other companies, such as offshore oil extraction, may allow the migration of professionals and suppliers to this industry that still does not exist in Brazil (offshore wind generation). As for maintenance costs, offshore wind equipment works autonomously with remote signalling and, when major maintenance is required, a specialized team is sent to the site".*

In line with what has been described by Venkatesh (2002), Martins et al. (2011) and Köberle et al. (2018), interviewee 7 also said that:

"the most important bottleneck for wind energy today in Brazil is not related to the wind industry or the type of generation itself but to the congestion of the transmission lines, which can make any type of wind generation project unviable."

On the other hand, interviewee 8 highlighted that:

> *"route 4 (onshore) is the best potion because it represents a well-established technology and more certainty in terms of obtaining the necessary wind speeds. Besides the existing wind speed information from wind atlases of the state where the wind farm will be installed (Ceará), is it possible for the entrepreneur to install a set of anemometers before building the wind farm, in order to know the seasonal characteristics of the wind in the specific location. On the other hand, for the offshore route there is no such possibility, which would impose risks if, after the installation is concluded, the wind quality is not the one that was forecasted during the preliminary studies. Additionally, route 8 requires a higher financial exposure of the wind farm developers (higher initial capital cost) when compared to the onshore route".*

The interviewee's statement is in line with what was mentioned by Menendez et al. (2011) and Samu et al. (2019), since if the wind quality is revealed to be different from that assessed during preliminary studies, it may lead to a loss of energy production and loss of efficiency of the wind turbines, negatively impacting the return on investment.

Expert 9 said that:

> *"the onshore alternative (route 4) is still the best option for the Brazilian scenario, since it mitigates the risks and uncertainties of the offshore route. Nowadays, the main problem involving offshore farms is the lack of regulation for this type of energy generation, as well as how little this option is discussed in the Brazilian political sphere, which makes me believe that there is still a long way to go before this type of energy generation is viable in the country. In addition, the first developer will need to overcome the risks of being the pioneer in a country where the rules of the game are constantly changing, especially in election years, even though it may be possible to make a profit. Additionally, Brazil has several remote regions that do not have access to electricity, so the country should give precedence to develop turbines to serve these regions on land."*

Interviewee 10 pointed out that:

> *"route 4 is the best option as it has a larger number of wind turbines, which would have less impact in case of damage to components that can't be found on the local market. In this case, the impact for the wind farm, in terms of total power, would be lower when compared to route 8. Furthermore, route 4 has already gone through the initial stages of the learning curve and can offer a tested and mature technology, which is already used in wind farms around the world. Regarding the impact to the community, route 4 offers the possibility of being installed in private areas, and the owners and families could have an extra income from the lease of the site for installation of the enterprise; this is another positive aspect of route 4"*

In line with comments made by interviewees 7, 9 and 10, in an interview to the Canal Energia website in October 2020, the president of the Brazilian Wind Energy Association (ABEEOLICA) emphasized that Brazil has the availability to generate energy through offshore wind farms, but regulatory barriers must still be overcome (Canal Energia, 2020).

CONCLUSION

With seven votes in favor, based on the technical, economic and financial aspects, as well as on the social and environmental impacts, risks and uncertainties, route 4 (onshore) was selected from a wide range of options as the best technological route for wind power generation in Brazil, at the chosen location. Even though the analysis was focused on a hypothetical wind farm in Ceará, it is arguable that this state is a good representative of a place with good potential for wind farms in Brazil, as was discussed in the introductory section. This helps to increase the external validity of this study.

This study leads to the conclusion that some factors present the same risks and uncertainties, regardless of the selected route: the ease of connection to the National Interconnected System presented itself as a problem more related to the congestion of the grid and the existence of obsolete transmission lines in the country than to the choice of a specific route. In addition, the location of the wind farm close to a substation is important to reduce costs and losses during power transmission, regardless of whether it is built onshore or offshore. On the other hand, while onshore wind farms generate impacts to the community due to noise, visual appearance, and the risk of collision with birds, offshore routes can cause damage to marine life, reefs and other economic activities such as fishing.

In general terms, according to the specialists, the advantages of route 4 (onshore) are that it is easy to install from a technical point of view, and to obtain the technology and the product. This route already has clear and valid legal and regulatory conditions, besides having a longer life expectancy when compared to the offshore route. This is basically due to the distance from the coast, where the wind turbines are less exposed to corrosion damage when located onshore.

On the other hand, considering the area required to build the onshore park: 80.13 Km^2, an area equivalent to the total area of the municipality of Eusébio (Ceará), one can predict that there will be conflicts with different stakeholders over land use, which may make the construction of multiple onshore wind farms unfeasible in the future. In this case, the offshore route is more suitable. Furthermore, in case Bill PL 4199/2020 is approved, it will be possible to expand the cabotage navigation sector in Brazil and the logistical costs for the implementation of offshore wind farms may become advantageous in comparison with the onshore route, since the transportation to the installation site depends mainly of vessels.

Experts generally agree that in the medium term (5-10 years) offshore wind energy will become a reality in Brazil, provided there is economic stability in the country, stable currency rates (since many components are imported) and the presence of clear regulations and easy licensing conditions for offshore wind projects. This would increase the interest of national and foreign investors to allocate resources in this type of venture in Brazilian lands.

The creation of an industrial cluster is a viable option to reduce the risks and uncertainties arising from offshore projects. On the other hand, as happened with Petrobras - which invested heavily in R&D to enable the extraction of oil from deep wells -, Eletrobras (a state-owned company) could carry out a pilot project for offshore wind power generation. Together with specialized companies and ABEEOLICA, academics from research centers and universities can develop viable prototypes of offshore equipment adapted to the wind and wave conditions of Brazil. As for the government, it can stimulate offshore wind power generation in terms of public policies such as subsidies and incentives for the purchase of equipment and construction of this type of enterprise, besides holding auctions and providing clear and transparent regulations.

Historically, as the availability of hydro energy in Brazil is seasonal, the government usually increases investments, creates public policies and specific auctions for other renewable energy sources only when reservoir levels are low and in a scenario of economic growth. If the country wishes to have greater energy security and less dependence on hydroelectric sources, it is necessary to make policies and investments with a long-term vision that allows for the expansion of other alternative forms of energy, such as offshore wind energy. A short-term, immediate vision focused on "putting out fires" does not contribute to an effective and efficient energy policy.

This study has many limitations. The analysis is focused on a specific region of the country. This was a deliberate decision, since the research design itself was better suited for a specific project on a specific location. The study is based on a quantitative-qualitative analysis and on expert opinions, as opposed to a classic, quantitative, technical-economic feasibility study. It is hoped that future studies will address these limitations. A large-scale study that takes into account other possible locations and regions, and/or a quantitative technical-economic feasibility study would be interesting venues for future research.

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