Wind farms at the end of expected lifetime

Current Status and Upcoming Options

January 2022

Empresa de Pesquisa Energética
MINISTÉRIO DE MINAS E ENERGIA
PÁTRIA AMADA BRASIL GOVERNO FEDERAL

(This page was intentionally left blank to proper alignment of pages during printing on both sides).

FEDERAL GOVERNMENT
MINISTRY OF MINAS AND ENERGY
MME/SPE

Ministry of Mines and Energy
Minister
Bento Albuquerque

MME Executive Secretary
Marisete Fátima Dadald Pereira

Secretary for Energy Planning and Development
Paulo Cesar Magalhães Domingues

Secretary for Electrical Energy
Rodrigo Lima Nascimento

Secretary for Oil, Natural Gas and Biofuels
Jose Mauro Ferreira Coelho

Secretary for Geology, Mining and Mineral Transformation
Alexandre Vidigal de Oliveira

GENERATION EXPANSION

Wind farms at the end of expected lifetime

Current Status and Upcoming Options

Empresa de Pesquisa Energética

A state-owned company linked to the Ministry of Mines and Energy and incorporated pursuant Law No. 10,847, of March 15, 2004, the purpose of EPE is to provide services in the area of studies and research aimed at subsidizing the planning of the energy sector, such as electricity, oil and natural gas and their byproducts, coal, renewable energy sources and energy efficiency, among others.

President
Thiago Vasconcellos Barral Ferreira

Director for Energy Economics and Environmental Studies
Giovani Vitória Machado

Director for Power System Studies
Erik Eduardo Rego

Director for Oil, Gas and Biofuels Studies
Heloísa Borges Esteves

Director for Corporate Management
Ângela Regina Livino de Carvalho

URL: http://www.epe.gov.brhttp://www.epe.gov.br

Headquarters
Esplanada dos Ministérios Bloco "U"
Ministério de Minas e Energia - Room744
Brasília – DF - 70065-900

Main Office
Praça Pio X, 54 – 7º Floor
20091-040 - Rio de Janeiro – RJ

General Coordination
Erik Eduardo Rego

Executive Coordination
Bernardo Folly de Aguiar
Thiago Ivanoski Teixeira

Technical Team
Anderson da Costa Moraes
Diego Pinheiro de Almeida
Flávio Alberto Figueredo Rosa
Glauce Maria Lieggio Botelho
Gustavo Pires da Ponte
Helena Portugal Gonçalves da Motta
Josina Saraiva Ximenes
Luisa Domingues Ferreira Alves
Mauro Rezende Pinto
Paula Monteiro Pereira
Robson de Oliveira Matos
Verônica Souza da Mota Gomes

No. EPE-DEE-NT-012/2021-r0
Date: January 24, 2021

DOCUMENT AND REVIEW IDENTIFICATION

Study Area	**GENERATION EXPANSION**
Study	**Wind farms at the end of expected lifetime**
Macro-activity	**Current status and upcoming options**
Domestic Ref. (if applicable)	

Reviews	*Issue date*	*Summary description*
r0	01/24/2022	Original issue

Table of Contents

1 INTRODUCTION

The first Brazilian wind farms were installed in the 1990s. The technology at the time used a hub height of less than 50 meters and turbines with less than 1 MW in capacity. That was the beginning of the Brazilian wind industry.

In 2002 the PROINFA - Incentive Program for Alternative Electricity Sources was created with the objective of increasing the participation of wind farms, Small Hydroelectric Plants - PCHs (Portuguese acronym) and biomass in the National Interconnected System (SIN in the Portuguese acronym). This program resulted in 1,283 MW of wind projects, corresponding to around 3,500 GWh (approximately 400 $MW_{average}$) of contracted energy for the year 2020 (Eletrobras, 2019).

Subsequently, the Energy Auctions[1] were the main mechanism for expanding the source, resulting in 746 contracted wind projects and totaling approximately 8,000 $MW_{average}$ of energy, in 22 auctions held since 2009, with a significant reduction in the prices of traded energy (EPE, 2020; CCEE , 2020). During this period, there was a significant advance in wind turbines technology[2], with an increase in the hub height, rotor diameter and greater turbine capacity. Recently, the free energy market (ACL in the Portuguese acronym) has also attracted investments in wind farms. All these mechanisms (PROINFA, Auctions and ACL projects) resulted in a current installed capacity of more than 16 GW (ANEEL, 2020) and with that, the share of wind power in the Brazilian electricity matrix jumped from 0.2% in 2002 to 9% in 2019, becoming the third source in installed capacity and the second among renewable energy sources. By 2029, this number is estimated to get to 17%, reaching around 40 GW (MME/EPE, 2020).

Considering that the PPAs (Power Puchase Agreements) for wind power in Auctions have, in general, a duration of 20 years, a term equivalent to the design lifetime of the equipment, it is clear that the projects in operation since the 1990s have already reached that age. The first projects contracted under PROINFA will reach that point within the next 5 years. By 2030, more than 50 wind farms will reach 20 years of operation, amounting to over 600 wind turbines and 940 MW of power.

Thus, the importance of discussing possible actions after this period is clear, whether they are maintenance, upgrading or decommissioning of installed wind farms. The countries that

---

[1] "Energy Auctions" are used interchangeably in this document as a reference to New Energy, Alternative Sources and Reserve Energy Auctions.
[2] On the progress of projects registered for the Energy Auctions, see the Technical Note available at: https://www.epe.gov.br/sites-en/publicacoes-dados-abertos/publicacoes/Paginas/Technical-Note-Wind-Projects-on-Energy-Auctions.aspx

pioneered the use of wind energy have already faced this challenge and, therefore, it is important to assess the lessons learned in those markets.

Therefore, this Technical Note aims to identify challenges, opportunities and possibilities for these plants.

This Technical Note is divided into 7 Chapters. End-of-life alternatives are presented in Chapter 2, considering the upgrading or decommissioning of plants. In Chapter 3, some important international experiences in this context are shown. The following chapters presents analyzes for the Brazilian market considering the situation of the current inventory of wind turbines (Chapter 4), commercial and regulatory issues (Chapter 5) and energy planning (Chapter 6) and, in Chapter 7, the conclusions of the study.

2 ALTERNATIVES AFTER LIFETIME

The life cycle of wind farms begins with the validation of the location where the project will be installed, its construction and operation phases, and down to the phase of completion of the expected operational life. At that point, there are two alternatives: extending the operation lifetime cycle (with or without repowering) or decommissioning and total shutdown of the plant (Ornelas; Tofaneli; Santos, 2019).

Like every electromechanical equipment, wind turbines have an expected operating lifetime planned in the project phase and that depends both on the durability of specific components such as generator, gearbox, blades, etc and also on the weather and operational conditions to which these turbines will be subjected throughout the operation period, such as wind speed and maximum gusts of wind, modes of operation, and other factors. Under the IEC 61400-1 standard, the design of a wind turbine is recommended to have a minimum service life of 20 years. This is the time considered in calculations, numerical modeling, laboratory tests with prototypes and mechanical resistance testing of components and experiments/observations in the field, assessing the history of faults and malfunctions of equipment previously developed by this same manufacturer, to be converted and expressed as a number of operating hours.

The weather and operating conditions considered in the designing of the wind turbine tend to differ from the actual operating conditions of the equipment. Thus, the operating lifetime of the equipment can be longer or shorter than the design lifetime. Another aspect is that, over the years, the operating efficiency of wind turbines tend to drop, as the wear and tear on the equipment implies an increase in maintenance frequency. For instance, Staffell & Green (2014) calculated that the capacity factors of 282 UK plants decreased at a rate of approximately 1.6% per year of operation.

Therefore after the operation period expected in the contract and with all maintenance steps having been carried out, it is advisable to carry out a technical assessment of the state of the wind turbines and other components of the wind farm and, with this result, carry out a study to establish the procedure to be adopted. Thus, as project approaches the end of its lifetime, the options are:

- Upgrading the plant through:
    - Extension of the operational lifetime of the turbines;
    - Partial repowering;
    - Full repowering.
- Decommission the plant.

It is emphasized that it is possible to adopt mixed solutions in which part of the equipment is decommissioned and repowered and part of which has its operational life extended. It is noteworthy that there is no consensus in the literature regarding the terminology for these alternatives, and some concepts can be mixed. In the following sections, the terminologies adopted in this study will be presented.

2.1 Upgrading

It consists of promoting interventions that result in increased productivity and efficiency of the wind farm, which may increase installed power, recover the original capacity of the equipment or solely improve the plant's control and automation equipment, thus improving the rates of generation availability. Lifetime extension and repowering are considered upgrading actions.

2.1.1 Lifetime Extension

Lifetime extension can also be called Retrofitting and involves the replacement of components such as generator, gearbox, yaw, picth or braking control mechanisms, and others, in order to recover or improve the original performance of the project, extending the operating time and life of its components for longer than initially designed.

According to Ziegler et al. (2018), lifetime extension is usually the option chosen when it is not possible, or it is economically unfeasible, to repower the plant. The main expected benefit is to increase the return on investment in a wind farm, extending its cash flow, but it should be considered that maintenance expenses will increase, given the greater need for repair actions on worn equipment. From an environmental point of view, using the equipment for a longer period of time can be beneficial.

According Chapter 3, many European plants had their service life extended. Furthermore, the study by Wiser & Bolinger (2019) indicates that North American wind farm owners estimate an operational life of around 30 years for their most recent projects. Many of them attribute this increase in life expectancy to the maturity and robustness of the technology and to a better understanding of operating and maintenance practices, wear and tear and the machines performance.

To extend the service life, it may be necessary to acquire new permits and establish new contracts, based on an assessment of economic, environmental and legal risks. It is also necessary to make sure that the components of wind turbines will continue to be available on the market, in order to guarantee the safety and operational continuity of the plant.

For the operational safety analysis, it is necessary to inspect the integrity of the turbine components in order to assess the risk of failure during operation. The probability of failure of each component must be at an appropriate level. In some cases, the condition of the equipment allows it to be used for a longer period of time, and in others, replacement is recommended. Corrosion, wear due to friction of moving parts, cracks and fatigue breaks in mechanical components, as well as shorts and overloads in electrical circuits are common damages in equipment subjected to long periods of continuous operation, which must be considered before deciding to change the wind turbine or to extend its service lifetime.

Aware of this issue, the International Electrotechnical Commission (IEC) is preparing the IEC TS 61400-28 standard - *Wind energy generation systems - Part 28: Through life management and life extension of wind power assets*, which will deal with the management throughout the operation and extension of the life of wind farms, with publication scheduled for the end of 2021. Guidelines on lifetime extension have already been published[3] and, in general, they deal with load analysis and simulations, mainly fatigue in the wind turbine and its components, based on equipment data and the history of operation and maintenance. According analyses, the possibility of extending the service life is determined and the necessary actions for the safe and efficient operation of the machines are estimated, such as, for example, the replacement and repair of some components, the frequency of inspections and maintenance.

2.1.2 Partial Repowering

Partial repowering occurs when it is possible to replace large components, allowing the wind turbine to increase its energy production. The replacement can occur by increasing the diameter of the rotor, increasing the installed power or the hub height, but keeping the same tower and foundation. As they are new components, the partial repowering ends up also translating into an extension of the service life of the turbines.

Partial repowering allows for an increase in energy production, and in the availability of turbines and a reduction in the loads to which they are submitted, in addition to increasing the reliability of the project. The investment costs are lower than in a full repowering; however, the performance gain is also smaller (Lantz; Leventhal; Baring-Gould, 2013).

[3] https://rules.dnvgl.com/docs/pdf/DNVGL/ST/2016-03/DNVGL-ST-0262.pdf;
https://standardscatalog.ul.com/ProductDetail.aspx?productId=UL4143

Some authors consider the replacement of the nacelle and rotor, keeping the foundation and the tower, as partial repowering (Lantz et al., 2013), while for others, this example would be considered as a full repowering.

2.1.3 Full Repowering

Full Repowering consists in the complete disassembly and replacement of the wind turbine assembly, disassembly/demolition of the towers, with the decommissioning of the entire original plant and the implementation of another configuration, allowing the installation of taller towers and turbines with greater power, providing greater capacity factors. According to IWEA (2019), repowering usually involves the construction of new foundations since, normally, the type of turbine is changed and it can also involve the replacement of some of the electrical equipment if there is an increase in the power of the plant. The repowering of a wind farm with new turbines takes the project back to the initial phase of its life cycle, requiring further feasibility studies, design and obtaining new licenses for construction and operation.

The main gains from the total repowering are the optimization of the space in the wind farm, the increase in its capacity, increase in efficiency, reduction of outages, and lower operating and maintenance costs. In addition, repowering can be done by taking advantage of part of the project's infrastructure, such as roads and connecting equipment, as well as enabling the sale or recycling of removed equipment. In addition, Wind Europe (2017) points out that newer turbines are able to provide network support services, ensuring better integration of the variable wind resource in electricity networks compared to older machines, contributing to the stability and flexibility of the system. When compared to investing in a new plant elsewhere, repowering has the advantage that the wind conditions, terrain and region characteristics are already well known (Baak, 2019).

Martínez et al. (2018) carried out an analysis of the repowering process of a wind farm in Spain in which thirty-seven 660 kW turbines would be replaced by seventeen 2 MW turbines, adding 40% of installed power to the project. When considering, on the one hand, the greenhouse gas emissions generated by the life cycle of the turbines, electrical system and substation and, on the other, the emissions avoided by the increase in electricity generation from renewable sources, the result indicated that the environmental balance was in favor of repowering.

Unlike total farm decommissioning and shutdown, repowering preserves local jobs and maintains the provision of land lease revenues to landowners and municipalities (local taxes from operating wind farms) (Wind Europe, 2017).

For total or partial repowering, it may be necessary to improve and widen the access roads for the traffic of heavy equipment since, in both cases, because of larger wind turbines, towers and blades; the cranes and disassembly and assembly structures used to exchange them must also be larger in size and load capacity than those used in the construction of the original project. The electric energy flow capacity in the region may limit the possibility of repowering and, therefore, should also be assessed. As the equipment will be removed, attention must be paid to the costs of disassembly, decontamination and preparation for the final disposal of the removed parts, in addition to the recovery of the locations.

The feasibility of an investment in repowering must be evaluated by the project owner and depends on the specific characteristics of each project, on the regulation and on the available opportunities.

Wake Effect

In partial or total repowering where there is an increase in the rotor diameter or the height of the hub, special attention must be paid to interference between turbines. The increase in interference affects the production of the wind farm, and the layout must be studied in order to make better use of the available energy. If there are plants nearby, with distances of up to 20 times the maximum height of the blade, considering all wind directions with a permanence greater than 10% (ten percent), the agreement of their owners will be necessary for the installation of new equipment or study that proves the absence of interference, as provided for in ANEEL normative resolution No. 876, 2020.

2.2 Decommissioning and Shutdown

In some cases, repowering or extending the service life is not attractive, so the last option is the decommissioning/shutdown of the plant. This decision consists of dismantling, decontaminating and preparing wind turbines and other components of the plant for final destination and disposal, and the legal requirements for safety and preservation or recovery of the environment must be met. All equipment related to the plant must be removed, which includes wind turbines, transmission lines, transformers, access ways and other systems. Sometimes the project owner has capital for total repowering of a decommissioned plant, but chooses to decommission the project and invest the capital in the construction of a new plant in another location. From an environmental point of view, this decision entails greater environmental impacts (Machuca, 2015).

The steps that guide the decommissioning of a wind farm vary according to its technical characteristics and operating time, as well as whether the purpose and objective of this action are intended for the future use and installation of the wind turbine in another location, or whether its purpose is to disassemble all components for reuse, resale, recycling or disposal. Decommissioning can be done in different ways: the towers can be demolished or the components can be dismantled to allow the parts to be resold, resulting in a more careful and slower process. The steps can be described as follows (CanWEA 2020):

Disassembly for Reuse – This procedure involves an inspection of all parts before removing the blades, nacelle, towers and plant control systems. It requires the assembly of support structures, a team with a multidisciplinary workforce (electromechanics, instrumentation and control, etc.), cargo handling cranes and all the logistics associated with electromechanical disassembly. After removing the equipment, all components must be properly packaged and preserved, with a view to shipment and future reuse at another site.

Disassembly for resale, recycling or disabling - In this type of decommissioning, the components are disassembled to be destined for other uses or discarded. The process is faster than disassembly for reuse, as it does not require the inspection, preservation and packaging steps to ship the components. Even so, an entire logistics of mobilization and subsequent demobilization of cranes, machinery and equipment is necessary.

Demolition - the towers are knocked down and the final objective will be to remove the destroyed components and cleaning the debris in the site. This process replaces the removal of individual parts, diminishing the need and costs of moving cranes, cranes and other equipment for assembling and disassembling of wind farms.

2.2.1 Legal and socio-environmental aspects

Regardless of the approach, it is advisable to prepare a decommissioning plan that includes the following activities:

- Survey with the environmental agency of applicable legal regulations and studies and measures necessary to mitigate the negative impacts of the procedure, including programs that benefited the local population and that will cease with the deactivation. The participation of the population in this discussion is desirable, as pointed out by Tereza (2019) in a survey carried out with ten state environmental agencies in Brazil.

- Verification of the conditions of access roads to the plant and service roads to allow the passage of structures and equipment, such as cranes, trucks and cargo handling equipment.

- Establishment of sets of temporary steel structures and crane around each turbine.

- In case of disassembly for resale, recycling or destruction or demolition, it is necessary to separate and correctly dispose of waste (item 2.2.2).
- Upon completion of the above-ground equipment decommissioning, depending on what is required by the environmental agency, it may be necessary to remove underground components (cables and junction boxes), in addition to the demolition and removal of the steel and concrete foundations, with subsequent land restoration.

According to the *American Wind Energy Association* (2020), many state and local governments in the US require decommissioning plans, the ultimate goal of which is to restore the area occupied by the plant in order to return it as close as possible to the conditions prior to its installation. Leaf (2019) proposes integrating decommissioning strategies into the design and installation, and that long-term impacts should be considered. This author also emphasizes that, in order to guarantee a sustainable removal process, the ideal is that any changes during the project's service life, such as upgrading, repowering or changes in the plant's administration, should always be registered.

The construction or expansion of roads located in the region where the wind farms are to be installed is considered a positive impact, as it improves the road infrastructure (Espécie et al., 2018). The presence of these roads can also benefit the shipment of decommissioned parts and equipment, however, the project owner should note the need for new expansions, if the traffic of larger vehicles is necessary. Another point that should be noted is the potential for producing dust and noise associated with the traffic of trucks, for which appropriate mitigating measures must be applied, like during the installation phase. On the other hand, upon decommissioning, the internal service roads to the plant may require environmental recovery, depending on the ecological conditions and the current and intended use of the land for the property.

Schreiner & Condonho (2018) emphasize that the shutdown of plants is not contemplated in the three-phase environmental licensing and suggest the creation of a fourth licensing phase with the issuance of an uninstallation license for this type of project. In a survey in which ten state environmental agencies responsible for onshore environmental licensing in Brazil participated, the theme of repowering and decommissioning of wind farms was considered relevant by all those agencies (Tereza, 2019). Regarding integrating decommissioning with environmental licensing, half of the participants were in favor of creating a decommissioning license, while the other half believed that decommissioning should be a step foreseen in the licensing of the operation. The assessment of international experiences showed that half of the participants prefer that the project owner contributes to a monetary fund aimed at deactivating wind farms and environmental restoration as a condition for issuing the installation license. Others pointed out that it would be important to draw up a deactivation plan prior to building the plant.

One issue that must be faced is who bears the burden of carrying out the decommissioning. In spite of the provisions of the Brazilian National Solid Waste Policy (PNRS in Portuguese acronym), discussed below, there is no specific regulation on the decommissioning of wind farms in Brazil. The matter ends up being dealt with on a case-by-case basis, through an agreement between the project owner and the owner of the land where the wind farm was or will be installed.

When analyzing the documentation of wind projects registered with EPE for technical qualification and participation in Energy Auctions, it appears that most of the contracts that regulate the right to use and dispose of the installation sites of wind projects provide that decommissioning is an obligation of the project owner. Thus, it is up to them, at the end of the contract or the operation of the wind farm, to remove all generation equipment and installations and return the land to the state as close as possible to that in which it was at the beginning of the contract.

Part of these instruments, on the other hand, treat decommissioning as the project owner's right. In these cases, at the end of the contract or the operation of the wind farm, two options are open to the project owner. First, the project owner may choose to remove the equipment and wind installations from the land, giving them the destination that suits him/her best. Alternatively, the project owner may leave the equipment and installations in the property, at which time it will be up to the land owner, if he does not wish to leave the equipment inoperative in his property, bear the financial costs and the logistics of decommissioning.

It should also be noted that a small portion of these contracts do not have provisions on decommissioning, that is, they do not state who (project owner or land owner) will be in charge of decommissioning the plant.

2.2.2 Waste Disposal

Although decommissioning generates a large volume of waste, it is noteworthy that the repowering and even maintenance of wind turbines also result in the exchange of parts, lubricating oil and grease, materials that need to be processed and disposed of properly, whether for resale, use in other ways or disposed of in landfills.

According to the *American Wind Energy Association* (2020), steel, copper and other metals, which make up the largest volume of a turbine, have a residual value and can be recycled.

Knutson (2019) points out that most electrical and metallic parts are recycled, while oil and grease-based lubricants and blades are discarded. Another possible destination for most parts of a wind turbine is its sale to wind farms in markets in Asia or Africa. It is estimated that the US will have more than 700,000 tons of blade material discarded over the next 20 years, and the world could dispose of millions of tons by 2050 (Bomgardner & Scott, 2018). In Europe, where space availability is restricted and waste management regulations are stricter, there is also a tendency for components removed from old plants to be resold to developing countries (*Institute for Energy Research*, 2019).

In the wind turbine, the rotor and nacelle (including generator, transmission box and other associated parts) have, mostly, metallic parts that are recyclable, with the exception of the blades. It is estimated that 80-90% of steel and cast iron can be recycled and that this rate reaches 95% for aluminum and copper. However, in general, all oils are incinerated (Zimmermann; Göblng-Reisemann, 2012; Martínez et al., 2018).

The steel towers, made up of only one material, are 98% recyclable. The reinforced concrete towers, on the other hand, can have different destinations: processing to separate steel and concrete (in which both can be recycled), use of granular concrete in roads and constructions, or final disposal in a landfill (Machuca, 2015).

There is a wide variation in international regulations on the depth that must be reached to remove the structures from the foundations of the towers, which can be 1.0 m in Australia; 1.2 m in Canada and range from 76 cm to 2.5 m in US local governments (Machuca, 2015). As most concrete foundations are about 5 m in total depth (*Institute for Energy Research*, 2019) and more recent ones can reach 11 m (*Contech Engineered Solutions*, 2020). It is reasonable to assume that much of the tower foundation will remain underground.

Overhead cables must be removed; however, underground cables can be kept in place, depending on the socioeconomic and environmental cost-benefit ratio of the excavation procedure, considering other uses and drainage of the land. International regulations also vary with regard to the removal of underground cables, but it is known that for some places it is mandatory. Where this is not mandatory, it is recommended that the ends of the cables must be buried at depths that can vary between 0.5 m and 1.2 m (Machuca, 2015).

Wind turbine blades are made up of a mixture of thermosetting resin (often epoxy) and fiberglass that, unlike other thermoplastics, cannot simply be melted and recycled (*Institute for Energy Research*, 2019; Bomgardner & Scott, 2018). This feature makes their destination an object of great concern for the environment. Martínez et al. (2018) estimate that 100% of the material in the blades is disposed of in landfills, similarly to what occurs with rubber, PVC and other plastics that make up wind farms.

One purpose indicated for the blades is the crushing and production of granules that can be used on floors, pallets and piping. After crushing, addition of adhesives and compressing, the residues from the blades can produce fire- and moisture-resistant panels (due to their containing fiberglass), ideal properties for the construction of commercial and industrial buildings. This type of insulating material for buildings can also be produced from the pyrolysis of epoxy-composed blades (Bomgardner & Scott, 2018), a technique also known here in Brazil (Guerrero et al. 2011).

In a survey of the advantages and disadvantages among the different destinations of decommissioned blades, Machuca (2015) concluded that reuse is restricted, but can be applied in playgrounds, provided that due care is taken; recycling, despite being the most environmentally favorable destination and allowing resale, requires crushing and application of a complex, expensive and experimental method; incineration, although it requires crushing, allows for the eventual use for generating thermal energy; and disposal in landfills, which despite seeming the simplest destination of those analyzed, is the one that causes the greatest environmental concerns. The same author demonstrates that, since the first decade of the 2000s, the disposal of blades in landfills has been discouraged in Europe. In addition, the *Institute for Energy Research* (2019) emphasizes that blades must be cut down before being taken to the landfill, and their administration may not have the adequate equipment to compact this material. Another concern is the storage capacity of landfills. As early as 2005, Germany banned the disposal of fiberglass-reinforced polymers, the material of blades, in landfills (Larsen, 2011). Thus, it is clear that blades represent the biggest challenge associated with the disposal of waste from wind farms. The other components, if properly treated, can be reused, resold or disposed of in a sustainable way.

In Brazil, the legal framework for solid waste management is the National Solid Waste Policy (PNRS), established by Law No. 12.305, of August 2, 2010 and regulated by Decree No. 7.404, of December 23, 2010, which provides on principles, objectives, instruments and guidelines relating to integrated management and solid waste management. One of the PNRS guidelines is to establish the following order of priority for the disposal of solid waste: non-generation, reduction, reuse, recycling, treatment, and adequate final waste disposal (Art.9º).

Taking the provisions of the Law as a parameter, solid waste generated during the decommissioning and deactivation of wind farms can be classified according to its origin as industrial waste (art. 13, item I, paragraph f), the generators of this type of waste being subject to the preparation of a solid waste management plan, as an integral part of the environmental licensing process for these projects (art. 20 to 24).

However, the analysis of environmental licensing procedures for wind farms in Brazil showed that the decommissioning of these projects has not been considered by most licensing bodies, and is therefore not included in the waste management plans prepared by project owners.

The PNRS also provides for shared responsibility among all those who participate in the life cycle of a product, including manufacturers, importers, distributors, traders and consumers, in addition to public agents. In that regard, the importance of instruments of this Policy stands out, such as sectorial agreements and reverse logistics, in the sense of defining responsibilities and actions of the players involved in the wind generation chain. Reverse logistics constitutes a "set of actions, procedures and means intended to enable the collection and return of solid waste to the business sector, for reuse in its cycle or in other production cycles, or other environmentally-appropriate final destination" (Art. , item xii). In this sense, the decommissioning of plants is an opportunity for companies that deal with demolition and recycling of materials, including the chance of generating jobs related to these activities (Knutson 2019; Ornellas et al., 2020). In Brazil, there are already companies specialized in the disposal of solid waste, including waste generated by wind farms.

Considering the possibility of decommissioning several wind farms in the country for the upcoming decades, it is essential that this process is carried out in a planned manner and that the disposal of the generated waste is environmentally appropriate, in order to maintain the sustainable nature of the wind power source.

2.3 Considerations for Choosing the Alternative

The decision to extend the service life, repower or decommission the wind turbines may be influenced by factors such as the remaining service life of the equipment, which may be different from that foreseen in the project; equipment maintenance cost; the termination of energy sales contracts; the end of the operating license term; the termination of land lease agreements and any operational issues.

It will be up to the project owner to consider what is the best decision. Some aspects that affect the decision are the assessment of equipment integrity, regulation on repowering, environmental regulation, requirements for extending the service life, possibility of renewal of land leases, technical and economic attractiveness of the land (including for other activities) and existing subsidies for both operating plants and new plants that may be built. Transmission assets have a longer service life than the machines, and the assessment must also include the transmission system. Another situation that can contribute to the decision is the guarantee of the supply of parts, such as rotors and nacelles, by the manufacturers.

According to Lantz, Leventhal, & Baring-Gould (2013), some critical factors for the attractiveness of repowering are energy sales prices, the durability and reliability of wind turbines, technological advancement, how much it will be possible to reuse the existing infrastructure and the resource wind available. In addition, environmental regulation and the existence of neighboring plants in the region downstream of the plant may affect the decision to repower with larger machines, as they may affect the energy production of the plants already in place.

Bona, Ferreira & Duran (2020) assessed the potential for repowering in Brazil and simulated different technical and economic scenarios to determine which parameters are most relevant for a repowering project. From a technical perspective, it was concluded that the repowering activity in Brazil should initially focus on turbines with less than 2 MW, currently distributed along 179 wind farms in the country, and that, in a scenario of continuous decrease of energy sales tariffs in auctions, repowering could become economically attractive, even before the end of the turbines' service life.

Each location presents different conditions, depending on orographic characteristics, wind behavior, layout of plant equipment, presence of neighboring plants or obstacles that can cause or suffer a wake effect. Thus, the operating costs and efficiency of the plants vary, as do the environmental and economic conditions.

If the site is suitable for repowering, the ideal age to replace the turbines must be assessed. If repowering is not possible, service life extension can be evaluated. The main question is whether operating costs will be balanced by the revenue from the energy that will be produced (Ziegler et al., 2018). In financial terms, it is important to consider the financial return on an investment in repowering against the return on investment in a new plant, for example. When considering lifetime extension, it is important to account for the expenses with more frequent maintenance and replacement of parts. If repowering or lifetime extension is not feasible, the option is decommissioning.

The possibility that the project owner should choose to adopt mixed options in their wind farms also stands out, in which part of the turbines are decommissioned and repowered and part has its service life extended, for example.

3 INTERNATIONAL EXPERIENCE

Europe, North America and Asia started energy generation activities from wind sources before Brazil. Thus, issues relating to the upgrading of wind farms and wind turbines and their consequences were also presented first, enabling prior knowledge, assessment of the best opportunities, regulatory experiences and good repowering and decommissioning practices.

To support this study, the international experience is presented as a way of identifying future challenges, learning about initiatives with good results and getting suggestions for procedures to be adopted or adapted to the Brazilian situation. The documents referenced in this international research show that regulatory and environmental aspects, financial subsidies and aspects related to technological evolution are the factors that decisively influence the initiatives developed in those countries.

3.1 Europe

According to *WindEurope* (2020), there are currently 34,000 turbines with over 15 years of operation, representing 36 GW installed onshore. Of this total, 9GW is estimated to have been between 20-24 years in operation and 1 GW to be 25 years old or more.

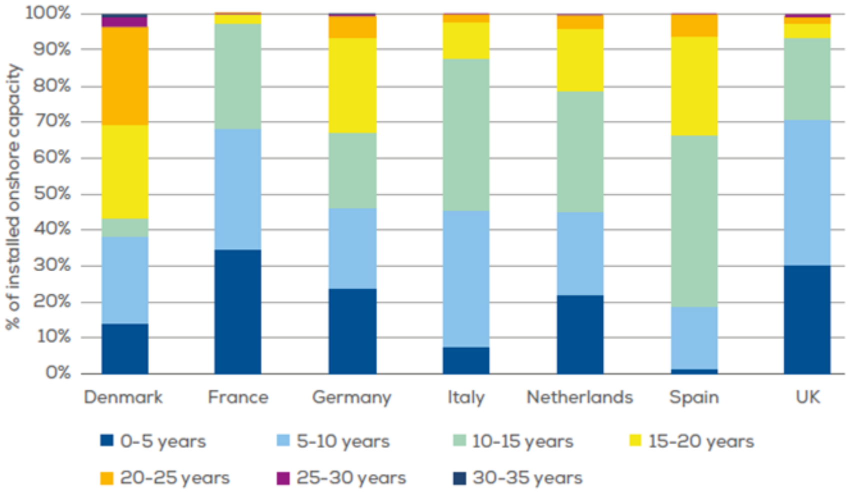


Figure 1 - Age distribution of turbines in selected countries (WindEurope, 2020)

For the European market, the *Wind Energy in Europe Outlook 2023* report (*WindEurope*, 2019) indicates that, of the approximately 22 GW of wind projects that will reach 20 years between 2019 and 2023, 18 GW will have their service life extended, 2 GW will be decommissioned and 2 GW will be repowered, increasing the installed power. According to this study, in 2019, 178 MW of wind farms were decommissioned and 185 MW were added through repowering, resulting from projects decommissioned in the last 2 years. The biggest increase in this potential took place in Germany, with other repowering initiatives also in Spain and Great Britain.

The study shows the main reasons for the low numbers: lack of regulation, authorization difficulties and high energy prices. According to the same report, the European Commission recommends that, in order to meet the 32% target for renewable energy, member countries need to be more specific in their regulatory measures for the implementation of renewable energy projects, in particular in regards to repowering. In general, in countries where there is no specific legislation for the shutdown of the plant, the installation site must be returned to its previous original conditions.

The current environmental rules in Europe are more restrictive than at the time of installation of the first wind farms, making repowering difficult in many places. In Germany, around 40% of existing projects will not be eligible for repowering due to regulatory changes and possibly will have their operational life extended or will be decommissioned.

In general, the life extension practice has prevailed in Europe, with a tendency to increase in the next years, until the tax subsidies or feed-in tariffs expire. Some countries (Germany and Denmark) have established requirements for inspection services and safety certification, covering structural components, while Spain and Great Britain, apply the same requirements for new projects, regardless of the age of the turbine (Ziegler et al., 2018).

According to the *Wood Mackenzie* study (2019), around 65 GW of installed capacity in Europe will reach the end of their 20-year service life by 2028 and 42 GW could represent commercially viable lifetime extension projects. Approximately 4 GW/year of wind capacity would be available for service life extension in the period 2019-2028, although the study indicates that, for small wind farms, upgrading may be less economically attractive. Larger farms, on the other hand, need to balance regulatory issues, financial risks and technical and operational challenges to make service life extensions feasible.

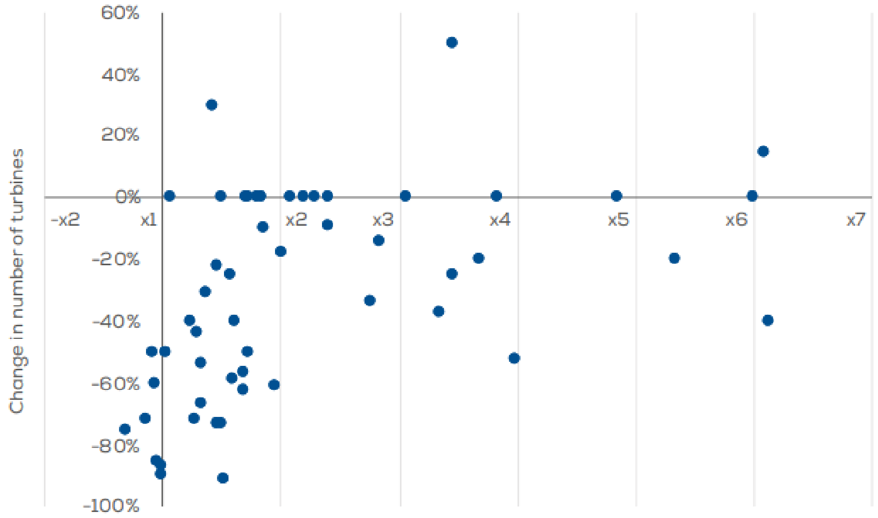


Figure 2 – Variation in installed capacity of repowered wind farms *(WindEurope* 2019)

Figure 2 shows the major modifications made to more than 60 European plants that have undergone repowering. These modifications were carried out on projects with different operating times, from 9 to 27 years, whereas in Spain the average time was 22 years. In Germany, repowering took place after 16 years of operation, on average, due to a bonus (until 2014) of 5 Euros/MWh for these actions (*Wind Europe*, 2019).

GERMANY - Farms commissioned before April 2000 received a fixed feed-in tariff rate until 2020, regardless of age. Those who extended their service life could continue to receive the incentive. Projects commissioned after this period, on the other hand, receive the tariff for 20 years.

From 2021, it is estimated that 4,000 MW installed will no longer benefit from the feed-in tariff, and by 2025, an average of 2,400 MW per year will lose this subsidy, causing the German wind industry to focus on large decommissioning and repowering scale, with replacement of current equipment with a long operating time by newer ones.

Given the current landscape, total wind power capacity in Germany will likely decline in 2021, for the first time since the Renewable Energy Act (EEG) was enacted, which is the main instrument to generate electricity from renewable energies in the country from the 1980s.

Turbine decommissioning in Germany is regulated by the Renewable Energy Sources Act (2017) and some provisions of the German Building Code.

DENMARK - Repowered plants can participate in "neutral energy" auctions, which aim to reduce carbon dioxide emissions (70% reduction target by 2030). In relation to decommissioning, local authorities have autonomy over the definition of these conditions already in the licensing for construction and operation. Decommissioning must start no later than 1 year after the end of the plant's operation.

In 2019, the repowering of 36 MW was contracted for *Wind Estate A/S' Overgaard II* project, to be carried out by Vestas. The contracting came from the country's second neutral energy auction in the year and is the company's fourth repowering contract in the two rounds of this type of auction, out of a total of more than 150 MW negotiated (*Energy Facts*, 2020).

SPAIN – Due to the incentives given to the first plants, which new ventures or repowering do not benefit from, life time extension has been preferred by project owners, because it amounts to a lower investment cost, although there are still areas available with good wind resource (Ziegler et al., 2018).

Spain establishes requirements for including decommissioning in the Environmental Impact Study, still in the project stage.

As for repowering actions in this country, an example is the *El Cabrito* wind farm, located in Tarifa (Cadiz), which went from 90 wind turbines of 330 kW installed in 1995 to 12 turbines between 1.5 MW and 3.0 MW. The old turbines with metal lattice towers were demolished. The dismantling involved the removal of all foundations, platforms, unnecessary access ways and 31 transformers, in addition to the removal and management of waste generated and the restoration of the landscape. The repowering project involved adapting the access ways, building new foundations for the turbines, installing cables and adapting the substation and control, as well as restoring vegetation (*Windfair*, 2019).

FRANCE - In 2020, France presented its National Energy and Climate Plan (NECP) for 2030. The country aims to reach 33% of renewable energy in its energy matrix by 2030 and, for that, the government seeks, among other actions, to prioritize the use of end-of-life plant areas for repowering. The repowering and decommissioning of plants in France, as well as the installation of new ones, are regulated by the Environmental Code (*Code de L'environnement*) (*Wind Europe*, 2020).

One of the first repowering initiatives in this country was in the Plouyé region, which was one of the first locations to implement a wind farm in 2002. In 2017, the project owner replaced the four 0.75 MW Neg Micon turbines for 2.3 MW Enercon models. The old turbines were dismantled and sent to recycling plants for recovery. All old concrete foundations were removed and the land restored to its natural state (*Kallista Energy*, 2020).

NETHERLANDS - It is one of the first cases in Europe where wind turbines with unit power greater than 1 MW are already being replaced by 4 MW ones. In the Netherlands, the decommissioning of wind turbines is covered by the Construction Decree of 2012.

The *Windplanblauw* project, scheduled for 2021, aims to replace 74 1 MW machines by 61 units, totaling 250 MW and quadrupling energy production. The Netherlands has also started the *Windparke Zeewolde* repowering project, with 320 MW of Enercon turbines, which will become the largest onshore wind farm in the Netherlands, comprising 70 turbines of 4.2 MW each, with a hub height of 220 meters. The project involves the replacement of 220 existing turbines, in addition to a new substation and two transformers (*Energy Watch*, 2019).

ITALY - Repowered plants can participate in energy auctions together with new plants, as a way to encourage the upgrading of existing plants. The repowering and decommissioning of wind turbines are dealt with in the Ministerial Decree of 10/09/2010, entitled *"Guidelines for authorization of plants powered by renewable sources"* (*Wind Europe*, 2020).

PORTUGAL - According to Simões et al. (2019), the wind capacity near the end of its service life in Portugal is in the order of 50 MW. However, the operating capacity of turbines with a nominal power of less than 2 MW, whose replacement is desirable, is approximately 690 MW. The authors point out that the plant reconfiguration process lacks specific regulation with regard to environmental issues, and it is important that the impact assessment reflects the accumulated knowledge, not only in the assessment carried out when the initial project was licensed, but also during the his environmental monitoring process.

In 2012, Iberwind started a process of repowering some of its plants, with investments of €65 million. With the replacement of older turbines by newer and more powerful ones, the company's installed capacity increased by 20%. Of its 31 wind farms in operation, that of Lagoa Funda, in Vila do Bispo, is one of the oldest (1998) and was repowered in 2011. The eighteen 500 kW wind turbines were replaced by six 2MW turbines, with larger rotors and hub height (*The Portugal News*, 2018).

UNITED KINGDOM - Most wind farms in the United Kingdom receive authorization to operate for a period of 25 years. At the end of this period, the turbines would normally need to be removed and the site returned to its previous use, in accordance with current environmental regulations. But a measure from the National Planning Policy Framework, released in July 2018, allowed local authorities to assess proposals to upgrade or renovate installed wind farms. By 2018, most wind farms that reached the 25-year operating limit were allowed to extend the operating period for up to an additional 10 years. In 2019, 22 plants were allowed to be upgraded, while only two were shutdown. On average, the repowering increased the production of the wind farms by 155% and reduced the number of turbines by 39%, while the height of the wind turbines increased by 90%. These changes are reported to have caused difficulties for local authorities to assess the visual impact of the new layout on the general public and local residents (RTPI, 2020). Decommissioning requirements are set out in the licensing conditions and, for permitting, decommissioning costs must be anticipated in the original installation plan. There is no specific legislation for the final disposal of waste from wind turbine foundations in UK.

SWEDEN - The Swedish Environmental Code does not allow the extension of the environmental license after its expiration; a new one is required, which may also be required when installing additional wind turbines. In any case, the environmental licenses also cover demobilization, requiring new licenses for the construction and operation of a new wind farm.

Näsudden in Gotland is the site of one of the biggest repowering projects in Sweden to date. Before, it had different types of turbines, regulated by several different permits. The repowering project layout aimed to maximize energy production with fewer turbines. Three new environmental licenses were granted, which regulated the dismantling/demolition of existing turbines, construction of new foundations and towers and installation of new turbines. In that country, environmental licenses cover demobilization, and new licenses are required for the construction and operation of a new wind farm (*Setterwalls*, 2020).

3.2 United States

Currently, in the United States, there is a growing search for partial repowering, due to Production Tax Credits (PTCs) for renewable sources, and also due to technological advances that increase the efficiency of turbines and their service life, in addition to reduce maintenance costs. Between 2017 and 2018, 23 projects were accounted for a total of 3,445 MW of capacity and 2,425 turbines that underwent partial repowering. Most of these modifications involved an increase in rotor diameter and replacement of nacelle components, with few changes in hub height and turbine capacity (Wiser & Bolinger, 2019).

Figure 3 displays the main changes of the upgraded projects, where the average increments are verified: 8.1 m for rotor diameter and 1.3 m for hub height, with minimal gains in power. In most of the projects, the existing towers were used and new nacelles were mounted on the same towers, or only the rotor and respective blades were replaced. Also according to Wiser & Bolinger (2019), the expectation is that in the coming years many projects will undergo total repowering, that is, their turbines will be decommissioned and replaced with new ones.

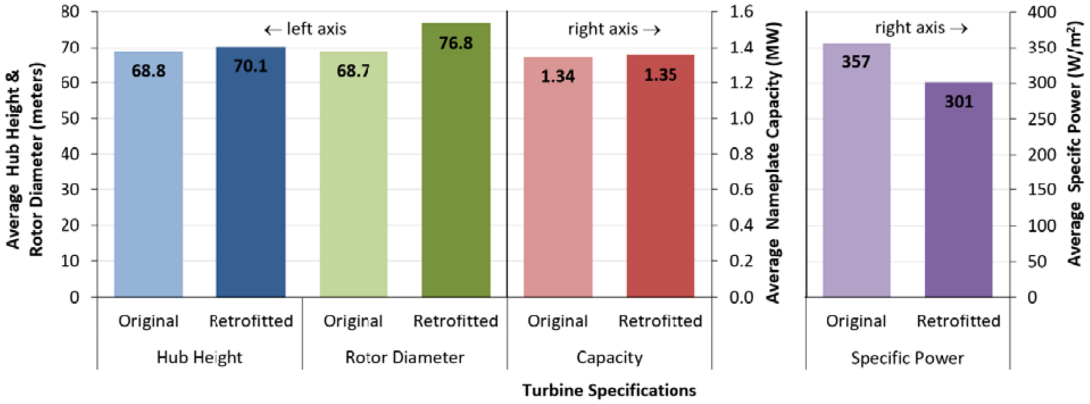


Figure 3 – Average changes in specifications of turbines repowered between 2017 and 2018. Sources: AWEA Wind IQ (2019); USWTDB (2019) *apud* Wiser & Bolinger (2019).

For repowering, the plants have to get new permitting. In the case of decommissioning, the total removal of the turbines is already foreseen in the licensing; for private properties, this phase is also defined in a contract, and in federal areas, it is governed by the Bureau of Land Management, but the project owner always shoulders the expenses. The plant area should be returned as close as possible to the way it was originally. Some material recycling measures are also well regarded in order to maximize the values of turbines, towers, foundations and connections with material recycling (AWEA, 2020).

3.3 India

In 2016, the Indian government adopted a policy to encourage the repowering of wind energy projects, aiming at the optimal use of energy resources. As part of this policy, the Indian Renewable Energy Development Agency (IREDA) offers lower interest rates on financing, in addition to existing tax and financial benefits that were previously available. (*Energy Economic Times*, 2018).

A study (IDAM INFRA, 2018) indicated that more than 10 GW of installed capacity with turbines less than 1 MW are in high quality class 1 sites. These sites offer the opportunity to double power generation with repowering turbines with a capacity between 2.5-3 MW and a capacity factor of 25-30% or more, compared to 15% for older models. This would amount to an estimated addition of 10-12 GW of installed capacity (*Saur Energy*, 2020).

3.4 China

The repowering market in China is expected to grow from 2023 on, when over 21 GW of installed capacity is expected to be repowered between 2019 and 2028. Repowering is currently still facing obstacles in China due to the expiration of feed-in tariffs. Repowering should grow as available places with good wind resources for new projects decrease. It is also estimated that, as subsidies are cut and the market for new construction slows, developers will focus on the repowering market for new investments (*Energy Global*, 2019).

4 BRAZILIAN WIND FARM SYSTEM

This chapter presents an overview of the wind farms located in Brazil according to the operating time of the projects, the installed capacity, the evolution of technological characteristics and the capacity factors, with a greater focus on the plants which, by 2030, will reach 20 years of operation.

Brazil has over 16,000 MW of wind power installed and in commercial operation. The oldest wind farm has been in operation since 1998 (ANEEL, 2020b). In addition to this, two others have been operating for over 20 years, totaling 17.5 MW. In 2002 PROINFA was created, which established generation contracts for 20 years and whose energy price is currently around BRL 500/MWh (ELETROBRAS, 2019). The first wind farms related to the program, which total more than 200 MW, started operations in 2006. As of 2011, the plants that won the 2009 Reserve Auction began operating. Between 2011 and 2020, new plants were installed that added more than 14 GW of power to the Brazilian electrical system and with an average contract price of less than BRL 200/MWh.

As shown in Table 1 and in Figure 4, over 50 wind farms, comprising more than 600 wind turbines and 940 MW of power, were installed by the end of 2010. These plants will exceed 20 years of operation by 2030 and will face issues related to upgrading or decommissioning planning in the coming years. The location of these plants is represented in Figure 5, along with the average wind speed of the location according to data from the Global Wind Atlas[4].

Table 1 - Installed power (MW) by period of start of commercial operation

Period	Time of Operation (years)	Added Power (MW)	Number of plants	Ranking by Power Ranges (No. of plants)				
				0 to 1MW	1 to 5MW	5 to 15MW	15 to 30MW	> 30MW
1998 to 2000	20 to 23	17.5	3	0	2	1	0	0
2001 to 2005	15 to 20	12.6	5	1	4	0	0	0
2006 to 2010	10 to 15	910.5	43	2	18	4	8	11
2011 to 2015	5 to 10	6744.9	266	3	4	32	194	33
2016 to 2019	1 to 5	7742.6	312	4	1	26	259	22

Source: Prepared by EPE based in ANEEL (2020b)

[4] Global Wind Atlas 3.0, a free application developed, owned and operated by the Denmark Technical University (DTU) in a partnership with the World Bank group, using data provided by Vortex, and funding from the Energy Sector Management Assistance Program (ESMAP). https://globalwindatlas.info

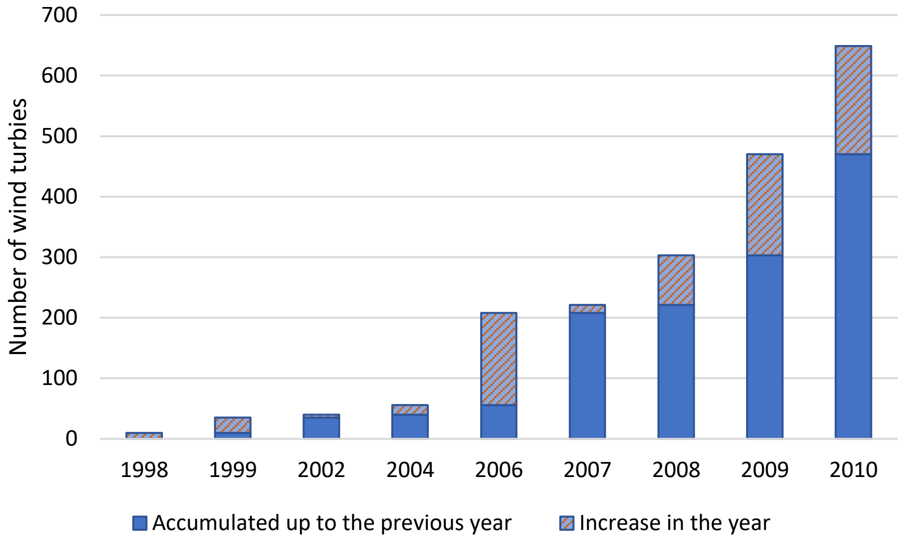


Figure 4 - Accrued number of wind turbines per year of start of commercial operation. Prepared by EPE based in ANEEL(2020a) and ANEEL (2020b).

Plants operating for over 20 years

According to data from ANEEL's SIGA (2020), 3 plants that have been registered with the agency have been in operation for over 20 years. All 3 have 500 kW wind turbines; 2 are located on the coast of Ceará (Taíba and Prainha) and 1 are located in Paraná (Eólio-Elétrica de Palmas).

According to Leão, Antunes, e Frota (1999), the Taíba and Prainha plants were built through a contract signed with the company Wobben Windpower Indústria e Comércio Ltda., as an independent producer, with the purchase of energy assured by COELCE for a 15-year period. These plants were authorized to be exploited by ANEEL Resolution No. 74, of March 25, 1998.

Eólio-Elétrica de Palmas, with an installed capacity of 2.5 MW, has 5 wind turbines and belongs to COPEL GERAÇÃO E TRANSMISSÃO S.A. Resolution No. 278, of September 28, 1999 authorized Centrais Eólicas do Paraná Ltda. to establish itself as an Independent Electricity Producer for regularization purposes, through the implantation of the Palmas Wind Power Plant, which had entered into operation in February 1999.

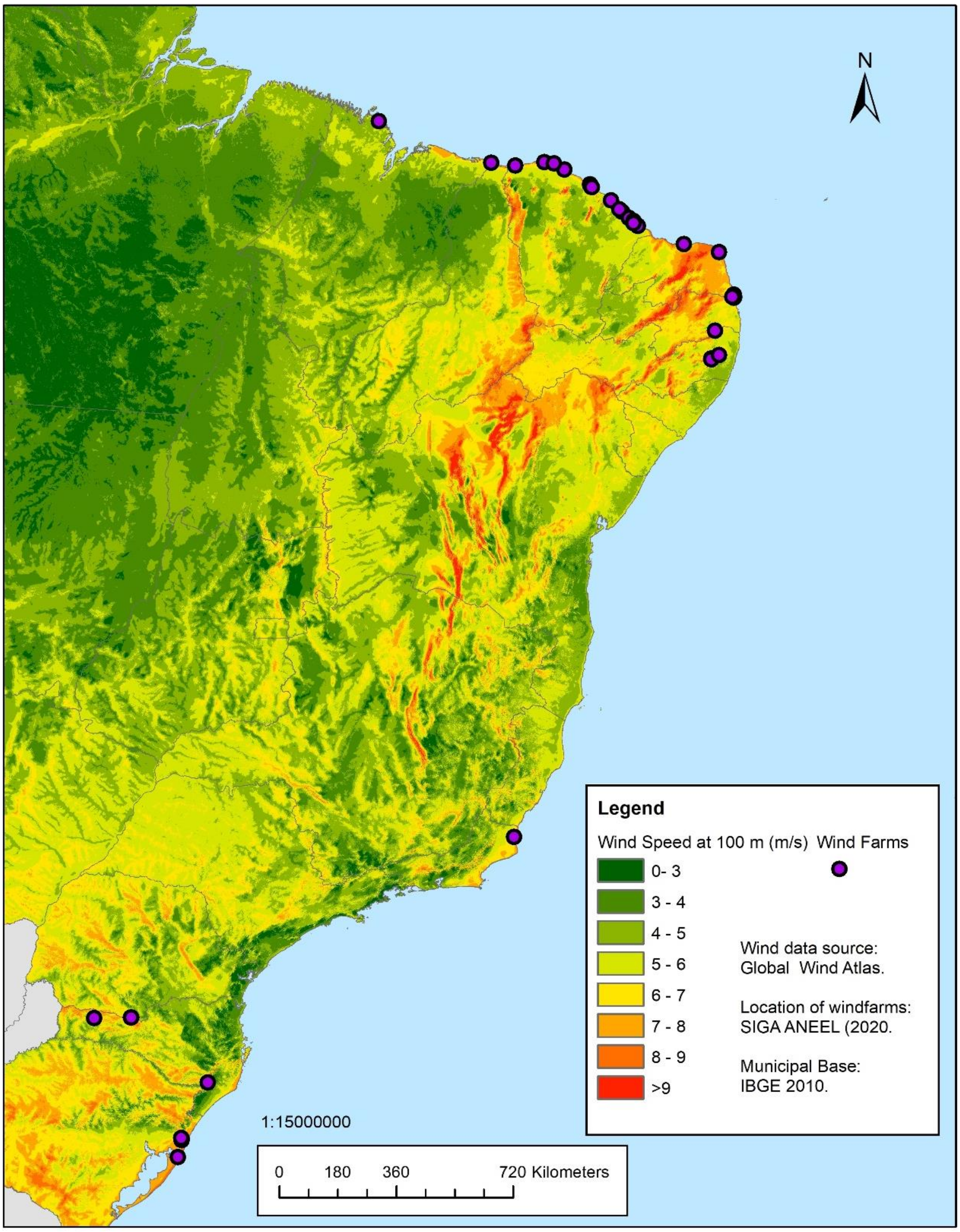


Figure 5 - Wind farms starting operation until 2010.

Sources: ANEEL (2020b), Global Wind Atlas (2020) and IBGE (2010).

During the preparation of this Technical Note, meetings were held with researchers and owners of the oldest wind farms, seeking to gather their views and plans. We would like to thank researchers Lívia Tavares Ornellas, Ana Paula Monção, Luzia Aparecida Tofaneli and Marinilda Lima Souza, and to companies Copel, CPFL Renováveis, Energimp, GE Renewable Energy, Iberdrola (Neoenergia), Omega Geração and Wobben Windpower for sharing their studies and opinions, thus contributing to this document.

In general, the project owners reported the good operating conditions of some plants, signaling the possible continuity of operation after the termination of PROINFA contracts, subject, however, to sufficient revenue to cover the high maintenance costs, which will depend on the commercial arrangements to be studied. Some generators mentioned the absence of regulation and an upgrading policy, although they recognize the challenge of competitiveness against new plants.

Some experiences of exchanging large components such as blades and generators in some machines were reported and partial repowering solutions were presented that have been carried out in other countries to improve the performance and extend the operating life of the equipment. To assess the possibility of major modifications, calculations of the loads the foundations will need to support are necessary. The carrying out of full repowering in other countries was mentioned, one of whose benefits is keeping up with technological evolution and taking advantage of a place where the local community is already used to the project; however, the current environmental regulation is more rigid and, in in some locations, full repowering may not be possible.

During these meetings it was also mentioned some positive experiences with the decommissioning of wind turbines, including the disposal and treatment of parts by specialized companies. On the other hand, cases of blades and towers being abandoned on plots of land were reported, which highlights the importance of regulations regarding decommissioning. In addition, it was mentioned that decommissioning can be costly and the time to carry it out and to restore the site to conditions from before the implementation of the plant can be long, thus confirming the need for early planning.

4.1 Equipment

Between 1998, the year in which the oldest plant currently in operation began operating, and 2020 there was significant technological progress. Figure 6 shows the average nominal power, height and diameter of the turbines used in the plants per year of entry into commercial operation, obtained through ANEEL's SIGEL and SIGA systems. The first plants have turbines with 0.5 MW of unit power and less than 50 m in hub height and rotor diameter. The turbines installed in 2019 have 2.4 MW power in average, 95 m of hub height and 112 m of rotor diameter. There is a big change, especially when comparing the diameters adopted in the first plants with those from 2019.

When analyzing the plants authorized to participate in the auctions in 2019 (EPE, 2020), an even greater difference can be verified: on average, the unit power of the turbines was 3.2

MW and some projects had turbines of more than 5 MW of power; the diameters averaged 128 meters and the average hub height was 111 meters.

Greater hub heights, rotor diameter and power allow for the optimization of wind resource leveraging, with consequent increase in energy production.

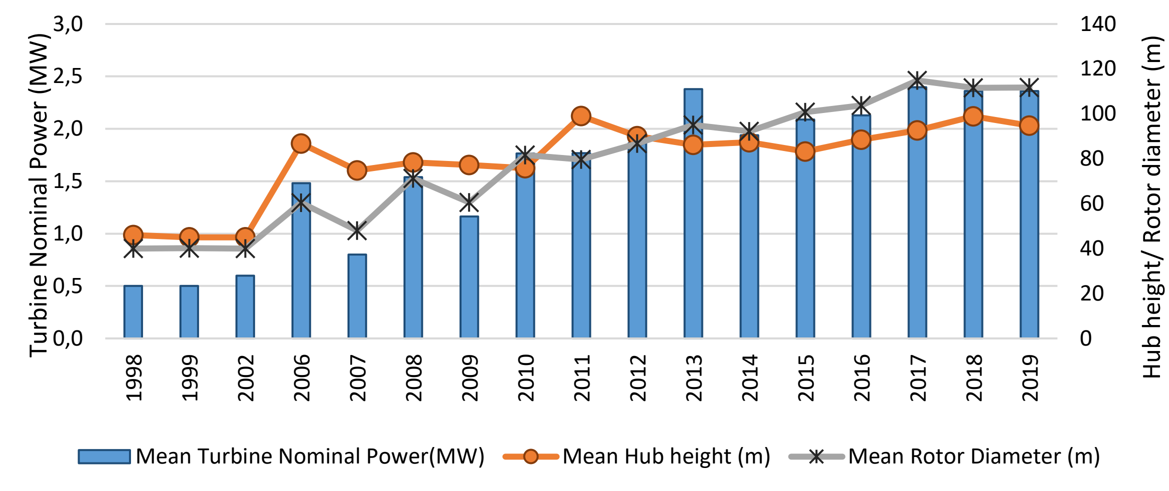


Figure 6 - Average turbine nominal power, hub shaft height and rotor diameter per year of entry into commercial operation. Based in ANEEL(2020a) and ANEEL (2020b).

Among the rules for technical qualification to participate in Energy Auctions, it stands out that wind turbines are required to be new, that is, not having been used before. Considering that the first auctions with participation of the wind source occurred when the European plants were going through the first repowering wave (chapter 3), it is understood that this rule contributed to avoid the use of demobilized machines and to the development of the domestic market.

4.2 Energy Analysis

In this item, some analyzes are presented in order to compare the productivity of wind farms contracted via PROINFA with the most current ones.

4.2.1 Comparison of generation with on-site wind

Like wind, wind farm output also varies over the years. It is interesting to assess whether this variation is due only to wind variability or whether there are operational issues as well.

The Figure 7, presents the monthly evolution of the average capacity factor index, calculated using the PROINFA plants installed between 2006 and 2010 and located on the coast of the Northeast region. In addition, it shows monthly wind energy rates. Analyzing these plots, it can be seen that, on average, the wind farms had variations consistent with the variations in the wind resource between 2012 and 2019, that is, in that period, no behavior caused by operational failures in the farms was noticed.

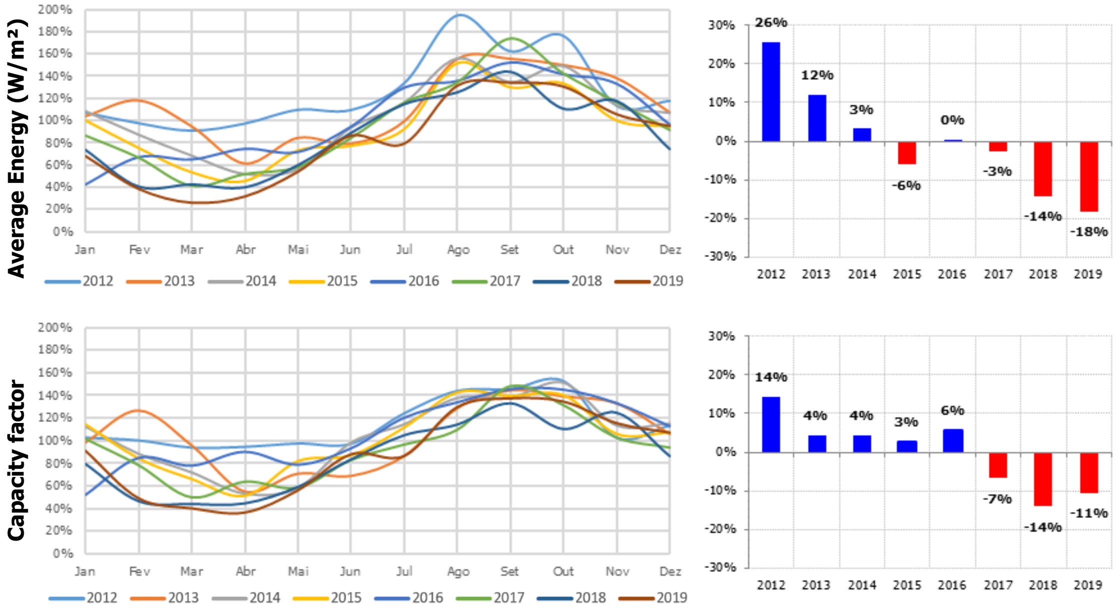


Figure 7 - Energy Rates and Capacity Factor - Northeast

The same analysis was carried out for PROINFA plants located in the South region, as shown in Figure 8. In 2012 the generation data do not match the wind. It can be inferred that one or more PROINFA plants had operational problems that year. However, in the following years, the average generation is consistent with the variations in the wind resource.

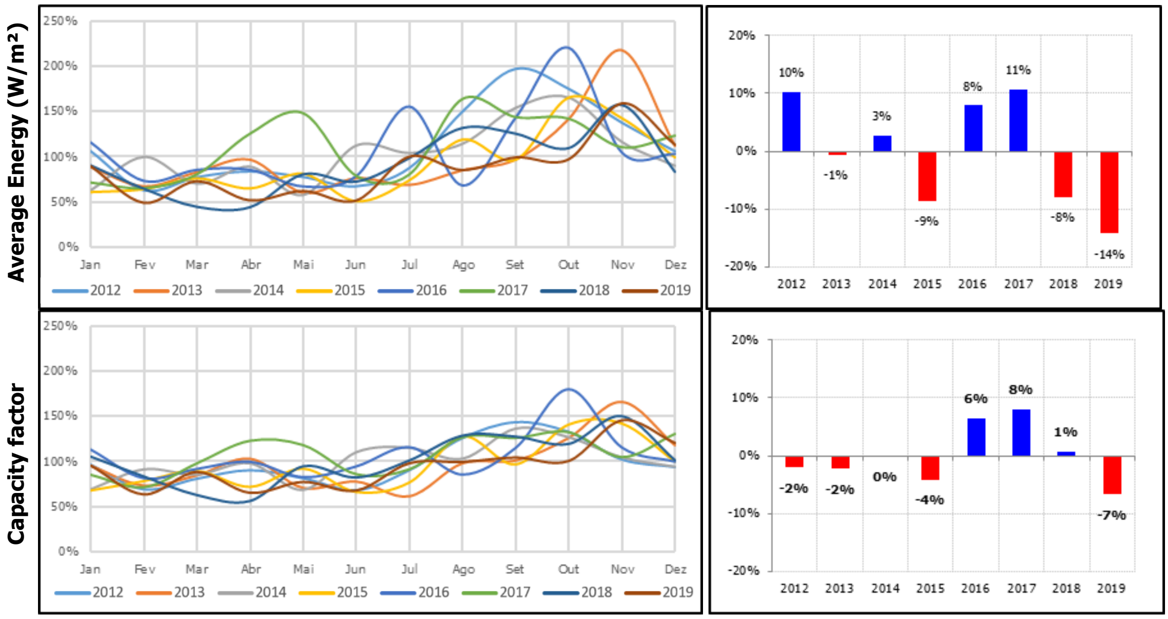


Figure 8 - Energy Rates and Capacity Factor - South

The data used in the above plots are available in the APPENDIX.

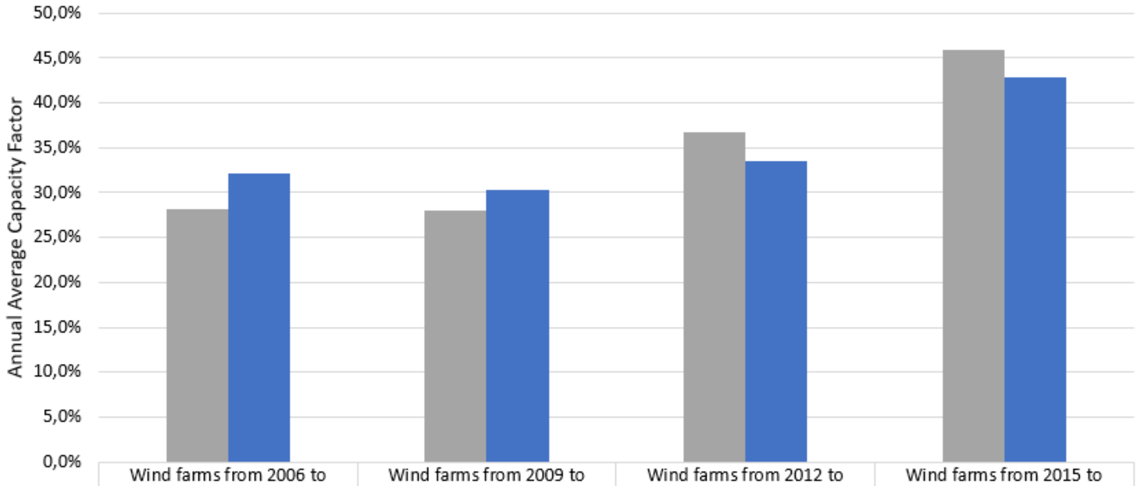
4.2.2 Comparison between plants installed in different years

The capacity factor of a wind farm depends directly on the characteristics of the location and the wind turbines. In relation to local characteristics, the most important are the wind speed profile, the turbulence of the place and the roughness of the terrain. Regarding the characteristics of wind turbines, the choice of models must take into account the power curve and how to optimize it (AMARAL, 2012).

For this analysis, the plants were selected according to the state in which they are located and the distance from the coast, so that the plants had been subjected to similar local characteristics. Capacity factors in the years 2018 and 2019 of the plants installed on the coast of the Northeast region and on the coast of the South region were analyzed. Those farms with zero generation in three or more months of the period were excluded from the sample composition process. In addition, wind farms that presented extremely low average annual capacity factors for normal operating conditions - below 10%, amounting to a prolonged situation of low energy generation and probably caused by technical problems - were also excluded. Each plant was rated according to its year of entry into operation. In this analysis, the dominant or representative technologies for each period were not selected, with only the year of entry into commercial operation being taken into account, regardless of whether the project used the most modern wind turbines available at the time or those with more consolidated technology. The most recent projects started to adopt new models of wind turbines for reasons of cost-benefit, but it is important to emphasize that the samples of each group can be composed by plants with different models of wind turbines.

In figure 9, the capacity factors of wind farms installed in the states of Ceará, Piauí and Rio Grande do Norte and located at a maximum distance of 10 km from the coast are compared, according to Figure 10.

In Figure 11, we see the capacity factors of wind farms installed in Rio Grande do Sul and located at most 22 km from the coast (Figure 12). In both plots, there is a trend for the average capacity factors to increase over the years, which may happen due to technological evolution.



	Wind farms from 2006 to 2008	Wind farms from 2009 to 2011	Wind farms from 2012 to 2014	Wind farms from 2015 to 2017
Average CF - 2018	28,1%	28,0%	36,7%	45,9%
Average CF - 2019	32,1%	30,3%	33,5%	42,9%

Figure 9 - Average capacity factor on the years 2018 to 2019 – Northeast Coast

Based on: CCEE, (2020), ANEEL (2020b).

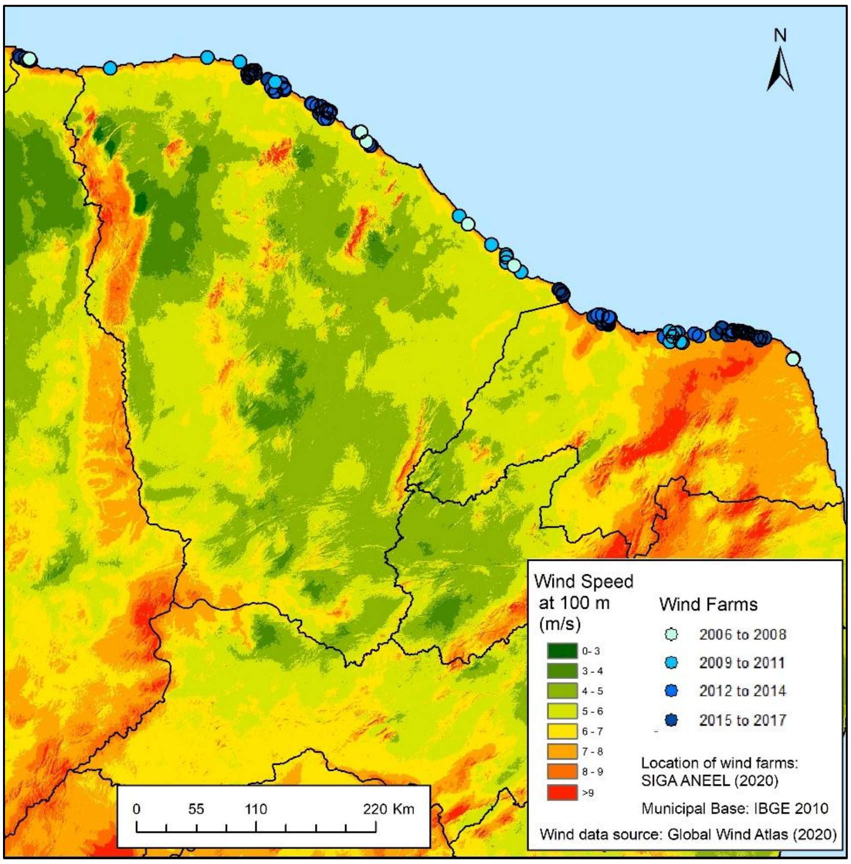
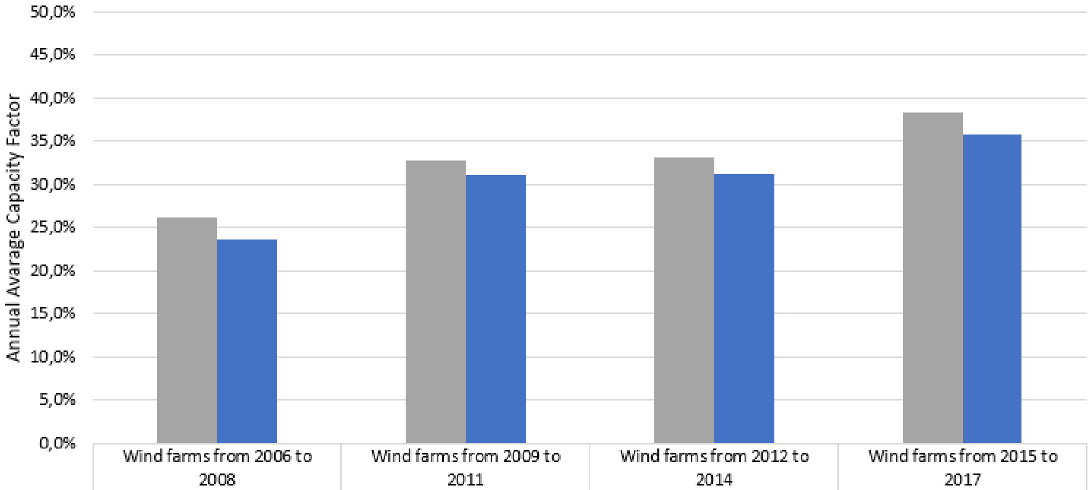


Figure 10 -Wind farms used – Northeast Coast



	Wind farms from 2006 to 2008	Wind farms from 2009 to 2011	Wind farms from 2012 to 2014	Wind farms from 2015 to 2017
Average CF- 2018	26,0%	32,7%	33,1%	38,3%
Average CF - 2019	23,6%	31,0%	31,2%	35,8%

Figure 11 - Average capacity factor on the years 2018 to 2019 – South Coast

Based on: CCEE, (2020), ANEEL (2020b).

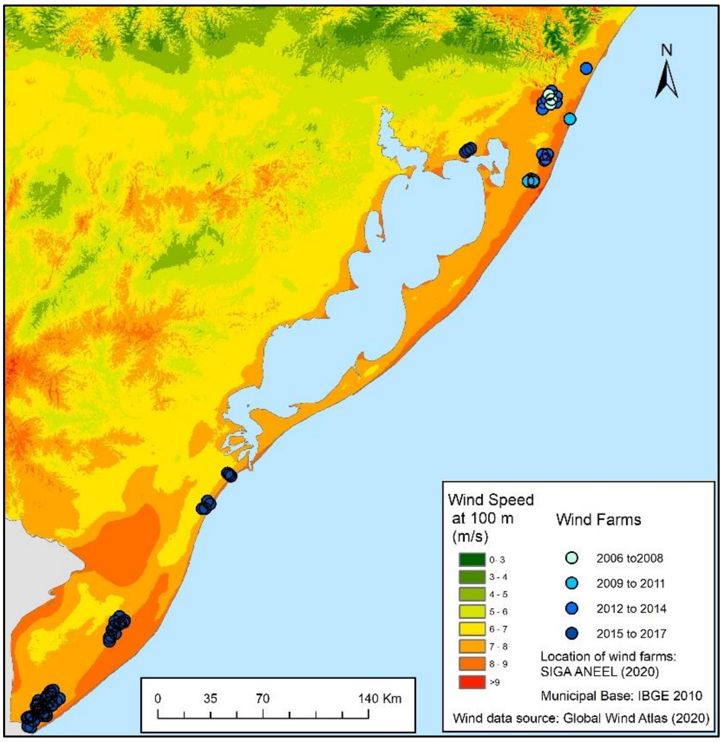


Figure 12 - Wind farms used – South Coast

Sources: ANEEL (2020b), Global Wind Atlas (2020) and IBGE (2010).

4.2.3 Comparison between old and current technology

As shown in item 4.1, the equipment installed in plants contracted via PROINFA are very different from current equipment, both in terms of installed power, and hub height and rotor diameter. Therefore, it is important to analyze the difference when using new wind turbines to replace the old wind turbines.

For this exercise, simulations were carried out using a representative location on the Northeast coast and another on the South coast. Estimates were made using the Windographer software with real wind measurement data every 10 minutes between the years 2012 and 2019. As it is a simplified study, the arrangement of wind turbines on the ground (layout) was not analyzed, no loss was considered, including the loss due to interference between the turbines, and the results represent the gross production of the wind turbines.

The objective is to simulate an existing wind farm, with an installed capacity of 42 MW, undergoing a **full repowering**, with replacement of all wind turbines, but without changing the installed capacity, given the possible restriction of increased flow capacity. Two models of wind turbines installed in wind farms in Brazil are used to represent the old wind farms. Note that, even for older plants, there are significant differences in the technology used. To represent the current wind farms, a model of wind turbine manufactured in Brazil and already installed in some wind farms during 2020 was used.

In addition to changing the turbine, the height of the wind collection was also changed, considering 80 meters for the old plants and 120 meters for the new one.

Table shows the characteristics of each simulation.

Table 2 – Wind turbines taken into account in simulations

	Turbine	Hub Height (m)	Capacity (kW)	Diameter of rotor (m)	Number of Turbines
Simulation 1	Enercon E-48	80m	810	48	52
Simulation 2	Vensys 77	80m	1500	77	28
Simulation 3	Vestas V150	120m	4200	150	10

The difference in power between the three wind turbines can be seen in the figure 13 below.

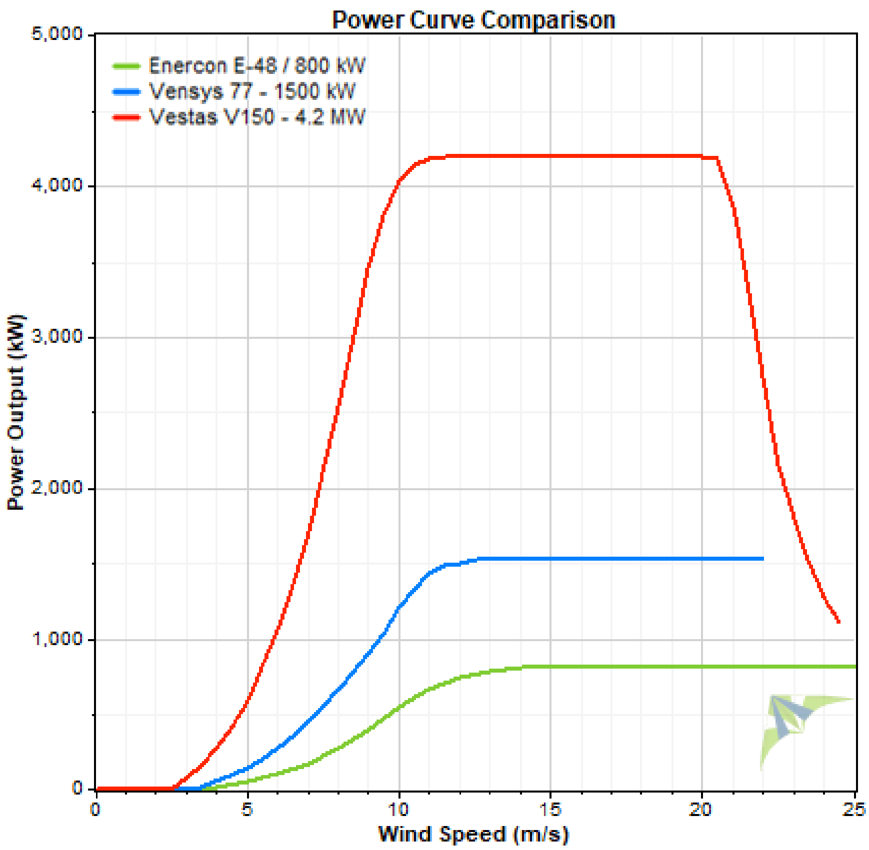


Figure 13 - Power curves used

For the coast of the Northeast, there was an average increase between 21 and 28 percentage points in the capacity factor of the new plant. Thus, a plant installed with current technology would generate, on average, **58% to 96%** more energy than previous plants. In Figure 14, it is possible to see the differences in the monthly and annual capacity factor of the plants.

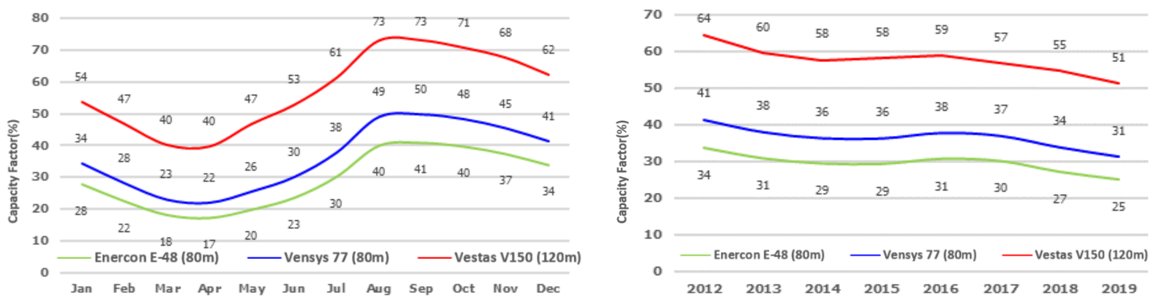


Figure 14 - Simulation for the Northeast Coast - Monthly and annual capacity factor

On the South coast, on the other hand, an increase of between 13 and 18 percentage points in the capacity factor of the new plant and an average increase in generation from **42% to 70%** were noticed.

Figure 15 shows the differences in the monthly and annual capacity factor of the plants.

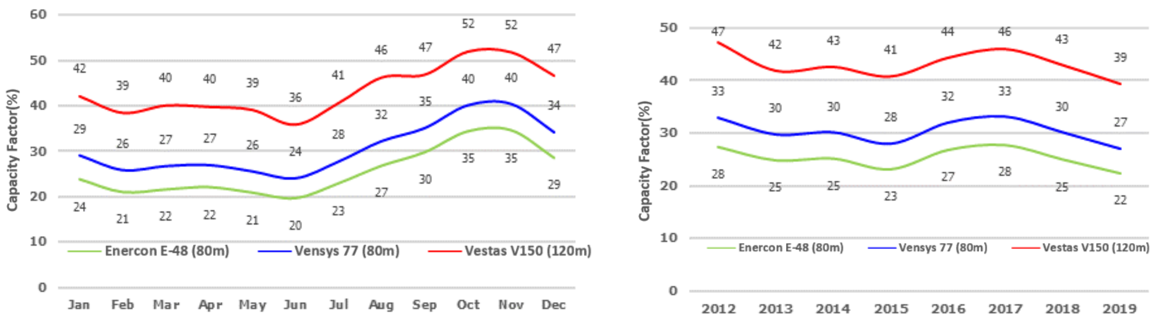


Figure 15 - Simulation for the South Coast – Monthly and annual capacity factor

Therefore, any repowering of these plants would result in greater energy production using fewer turbines.

5 REGULATORY AND COMMERCIAL ISSUES

When deciding on repowering or extending the service life of wind turbines, it is important to consider the regulations relating to energy trade. This chapter presents information on current regulations applicable to wind farms that trade energy both in the free and in the regulated market.

Energy trading is governed by Law No. 10,848/2004 and by the rules of the Granting Authority and the Regulator, with emphasis on ANEEL Normative Resolution No. 876/2020, which establishes the requirements and procedures necessary to obtain authorization for exploitation and alteration of installed capacity of wind power plants (and other sources).

In the Free Market (ACL in Portuguese acronym), contracts are negotiated between the parties and usually have shorter terms than in the ACR, and the project owner is responsible for managing them, including with regard to the commercial arrangements necessary for the amortization of investments throughout the project lifetime. Therefore, energy from a wind farm in the ACL can be traded with different buyers throughout its commercial operation.

In the Energy Auctions, the contracts for the wind source are for 20 years. Therefore, having been traded at an auction, there is no legal impediment for the plants to continue to operate after the final term of the contracts, as long as they are regularized before the granting authority and other bodies.

Thus, it is worth highlighting the difference between the timeframes of the energy sales and authorization contracts. While the former are usually for 20 years in Energy Auctions, authorization grants are valid for 30 to 35 years. Therefore, once the contract is ended, the project owner can still continue operating his plant for a few additional years, leaving the definition on the sale of energy in this period remaining.

The sale of energy after the end of the contract, in the simple case of extension of the plant's service life, without changes, can take place in different markets: in the ACR (Portuguese acronym for Regulated Market), ACL (with shorter term contracts) or even without a contract, just settling its production to Spot Price (with greater financial risk). In any case, the plant's operating and maintenance costs must be considered in comparison with the expected revenue.

In the case of the ACR, this sale could eventually take place through existing energy auctions, although these auctions usually only consider the participation of thermoelectric plants. However, in the case of upgrading of wind turbines, the way to trade energy involves understanding the technical change that will be carried out in the project, the project's service life, the stage and the type of contract to which it is submitted. It stands out here that, as with projects in the free energy market, any change in technical characteristics must be preceded by approval by ANEEL, through the process disciplined by MME Ordinance No. 481/2018.

According to Law No. 10,848/2004, parts of existing projects that may be expanded, restricted to capacity additions, can be considered as new generation projects for participation in Auctions. This happens with thermoelectric projects, for example, when a machine already in commercial operation is replaced by one with greater power. In this case, safeguarding the portion committed in the previous contract, the increase in capacity is understood as new energy and can be sold in Auctions for this purpose. However, it is important to highlight that an power plant whose energy has been sold in Reserve Energy Auctions, even if the exchange of a machine during the grant period has occurred for reasons of necessity, it cannot have its excess energy sold, as the Reserve Energy Contracts establish that projects must be dedicated and, therefore, their energy can not be traded in another way.

It may be interesting for some project owners to carry out the repowering of machines even before the end of the current authorization period and to request an extension of the grant already with machines capable of meeting long-term demands. It is also up to the project owner to assess whether the creation of new plants is more advantageous, with the decommissioning of old plants, or to carry out the total repowering of the old plants, with the exchange of all the existing machines.

Also noteworthy is a change recently introduced by Provisional Measure (MP in the Portuguese acronym) No. 998/2020 when dealing with reductions in tariffs for the use of electric transmission and distribution systems (TUST and TUSD in Portuguese acronym) for certain sources, including wind power. The MP provides for the maintenance of discounts for new projects and the amount plus installed capacity, provided that the request is made within 12 months and that the operation starts within 48 months after the grant (new or altered). Such a measure may represent a benefit for (partial or full) repowering that results in additional power. However, the MP restricts the discount to the timeframe of the grant, as it does not apply in the case of an extension. Additionally, the validity of this measure will depend on its maintenance in the final text and the conversion of the MP into Law, which had not yet taken place as of the completion of this Technical Note.

As can be seen, there are a number of possible configurations that should be assessed by the project owner, in addition to the cost-benefit ratio of upgrading the generating complex, and which could make the project more viable.

At the same time, the importance of clearly defining the regulatory process to be followed by those who opt for modernization is stressed, including the possible permission to participate in ACR auctions, in order to avoid ambiguity of understanding.

Additionally, it must be considered that the current situation differs from that of PROINFA, given that new projects are very competitive and have had a significant participation in energy auctions and in the free market, at decreasing prices. For this reason, the potential extension of old contracts to current prices is not seen as attractive and, even at lower prices, they should be competitive with new plants. This reinforces the notion that the decision to extend the service life or repower a plant must be made at the expense and risk of the project owner, who will assess the investment and maintenance costs necessary for the continuity of the operation, against current energy prices.

With regard to the decommissioning of the plant, there is still little legal and regulatory clarity on the responsibilities for dismantling and disposing of equipment, as discussed in section 2.2.1. In addition, ANEEL's Normative Resolutions No. 389/2009 and 876/2020, for example, establish a series of requirements necessary to obtain an authorization grant, in addition to the rights and duties of generators, including with regard to maintenance and conservation of the equipment in perfect working condition, but do not provide for rules for the decommissioning of the plants.

6 CONSIDERATIONS RELATING TO ENERGY PLANNING

As reported in the previous chapters, the oldest Brazilian wind farms are approaching twenty years of operation, a period in which the service life of the equipment begins to end. Although plants can be technologically upgraded, the project owner's decision results from an economic analysis based on current regulations and opportunities.

For energy planning, a series of questions arise in view of this situation: can demand rely on the supply of wind energy from these end-of-life plants? If the plant is decommissioned to have the site used for a new layout, does the land where the plant is located allows for greater leveraging of the wind resource under the new technological condition? What are the operational effects brought to the Main Grid, considering the energy supply criteria? How would the system and the operating marginal cost be affected by the deactivation, even if gradual, of the large number of plants that are economically non-repowerable or non- operational beyond their original service life?

The replacement of energy generation sources at the end of their (technical or economic) life by new projects requires predictability so that investments can be made at the necessary time, so that the new offer is available when the system requires it. Thus, mapping the amount of existing wind power supply that can be upgraded or that should be replaced by other sources demands a time window in tune with the sector's decisions. Actions in the necessary time require the allocation of financial resources, environmental licensing, availability of connection to replace this supply, among others. Therefore, the importance of this issue must be recognized and the demands that arise and unfold from the point of view of energy planning must be raised and explored.

In the Ten Year Energy Expansion Plan (PDE in the Portuguese acronym), for example, unlike thermoelectric plants, the output of wind farms is not yet considered in this planning timeframe. But, given the relevance that this topic should gain, the necessary advances for this consideration in future plans are already being studied by EPE. For that, the issues raised above are necessary.

With regard to meeting the demand, the question that arises is whether the generator will consider that the income obtainable from the settlement of this existing energy, whether at the spot price or through new sales contracts for existing energy, will be satisfactory and able to cover the expenses required to maintain their business and extend the plant's operating life. It is understood that the ACL may represent a potential market for the energy generated after the termination of contracts in the ACR, signaling a positive response to these questions, but other elements must be included in this assessment.

It is commonly known that operation and maintenance costs rise over time, due to the need for a greater number of activities to recover worn equipment, a situation that grows worse over the asset's operating time. However, the possibility of continuing the plant with the configuration of existing wind turbines renewed by replacement or retrofit, gives rise to the issue of factory availability of spare parts for this equipment at the time the decision is made. Many of the installed wind turbines are from the first generations and do not even continue to be manufactured due to the technological leap made in wind engineering. The exchange of blades or the generator set by those from other manufacturers is also a high-risk activity, as the responsibility for performance and operational safety becomes a risk for both suppliers and plant operators. Who would guarantee the safety and operation of a wind turbine made up of different equipment designed and tested for unique conditions and by different manufacturers?

If the decision to replace is made, would there be enough time to amortize the investment? The decision also involves valuing the knowledge of the wind resource obtained throughout the plant's operation, reducing uncertainties regarding future generation, in any alternative. If that is not considered economically interesting, once the contract is terminated, there would be no commitment to supply energy, which arouses the immediate attention of the planner. At that time, the energy contribution of this plant could no longer be counted on.

Regarding the network in which the plants or sets of plants are connected to the transmission grid, in many cases, the project owner would be responsible for the decommissioning in the event of wind farm deactivation. However, in other cases, it is incorporated into the main grid and, in case of deactivation of the wind farm, the grid would not necessarily be decommissioned. It is important to consider that transmission assets have a longer service life than wind turbines. A question that comes up is whether the power grid, under the responsibility of SIN, designed and operated for power injections in the plant to be deactivated, would require additional investments as a result of the plant's demobilization. The network is sized both for generation flow and to increase reliability. So there may be instances where some minor boosting is needed. This should be analyzed on a case-by-case basis, as the grid evolves over time in terms of topology, load and other generations.

In a way, what can be seen are narrow margins for readjustment of an existing plant due to its technological lock-in, understood here as the technical, economic and constructive regulatory framework on which the installation of the plant was based. This aspect is a good issue on how the planning should consider the final years of supply of contracted plants against the guarantee of supply from SIN.

Although there is time until the end of most contracts, allowing for careful analysis by the project owners, planning must foresee and anticipate issues and actions, which will become increasingly relevant, given the number of wind projects made possible in the past 20 years. Thus, the answers to the questions formulated in this Technical Note should reduce uncertainties for planning.

7 CONCLUSIONS

In the next 10 years, many Brazilian wind farms will exceed 20 years of operation. These plants must choose between: (i) continue operating with only a few adjustments to its equipment; (ii) continue operating while maintaining the foundations and tower, but replacing components such as rotor, nacelle and drive-train; (iii) decommission the wind turbines from their foundations up and use the site to install new equipment; or (iv) completely shut the plant down. Actions for upgrading and decommissioning of wind turbines usually carried out when wind projects near the end of their operational life were pointed out, and the advantages, barriers, points of attention and other factors that may affect the decision of the owner of repower, extend the service life or deactivate their equipment were assessed for each alternative.

Chapter 2 presents which repowering or service life extension actions allow the use of infrastructure and of a location where the wind behavior is already well known. The exchange of equipment for more modern ones makes it possible to optimize the use of the wind resource and reduce maintenance costs. Shutdown is usually the option adopted only when service life extension or repowering is not feasible. The choice of the most appropriate action for each venture, by the project owner, includes technical, economic and regulatory assessments. Important attention must be given to the environmentally adequate waste disposal, which occurs not only during deactivation, but also during repowering or even in the maintenance stages, in order to maintain the sustainable character of the wind power source. Alternatives for recycling, reuse, treatment and final disposal of waste were identified.

Then, international experiences on the extension of useful life, repowering and decommissioning were reported, showing that regulatory, environmental, financial subsidies and those related to technological evolution are the factors that influence the initiatives developed in the countries studied. The main changes adopted in the experiences of full and partial repowering and the existence or absence of specific regulations related to the actions were pointed out, with emphasis on Europe, where there was already a first end-of-life cycle for wind farms.

Chapter 4 points out the situation of Brazilian wind farms, pointing out their operating time and technical characteristics, showing the relevance that upgrading actions should gain in the next 10 years, given that more than 50 wind farms, with installed capacity that exceeds 900 MW will have already surpassed 20 years of operation and contract, and almost all of this amount comes from PROINFA contracts, so the owners of these plants will soon have to face decisions about the end of their operational life.

Due to technological progress, a case study was carried out estimating the possible energy gains with the replacement of old wind turbines by modern ones, based on some of the first plants installed in the Northeast and the South. The simulation results indicate that the total repowering, maintaining the plant's power, allows gains between 42% and 96% in energy production, with a significantly smaller number of turbines. The fact that many of the locations chosen for the implementation of these projects are in regions with wind that are clearly favorable to energy generation may also point to the advantage of continuing to operate these projects. There is also the benefit of already knowing the behavior of the wind resource, which reduces risks and uncertainties both from the point of view of construction and energy generation. Another factor is that, oftentimes, the project already has a high level of acceptance in the community where it is inserted, for, among other aspects, it brings economic dynamism to the region.

Chapter 5 presents the regulations dealing with the sale of energy from wind farms. It is envisaged that the sale of energy from repowering or extending their service life can occur in both the free and regulated market, requiring each project owner to assess the possibilities and economic benefits of each alternative. Decommissioning must be included when the option is to shutdown part or all of the wind farm and for total repowering. However, there is a lack of legal and normative instruments to guide these procedures, making it essential to plan and appropriately dispose of the waste generated, in order to maintain the sustainable character of the wind industry.

Chapter 6 presented several questions about how the decision to upgrade or decommission should affect energy planning, which will become even more relevant in the next decade, when many wind farms will complete their project life. There are still some indefinitions that bring uncertainties to planning and, therefore, this Technical Note seeks to indicate them, in order to stimulate discussion on the subject.

As stated above, we have concluded that issues relating to the end of the operational service life of wind farms will become increasingly relevant in Brazil and the players should start to plan for that. Economic assessments in view of possible regulatory and technological opportunities will be preponderant in the decision of project owners. Special attention should be paid to decommissioning and waste disposal activities that need to be planned in advance.

8 FUTURE STUDIES

Not many studies have yet been carried out on issues related to the operational end of life of wind farms in Brazil, so there are numerous possibilities for future studies. Each of the themes dealt with in this Technical Note can be deepened in other papers. We stress the importance of studies that address the following aspects:

- Economic analysis of the possibilities, considering the different types of contracting, the service life of each component, maintenance and decommissioning costs, in addition to comparing costs with other sources.
- Study the benefits and challenges of each alternative for the country as a whole and for the electricity consumer (including the environmental issue).
- Assessment of the consequences for the Brazilian Electric System, including in transmission planning, of the deactivation of many wind farms.

9 REFERENCES

AMARAL, B.M. Modelos VARX para geração de cenários de vento e vazão aplicados à comercialização de energia, Master's Thesis, PUC-RIO - Pontifícia Universidade Católica do Rio De Janeiro, Accepted on 14/09/2011, Certified on 03/08/2012.

American Wind Energy Association – AWEA. Decommissioning. 2020. Available at: https://www.awea.org/policy-and-issues/project-development/state-and-local-permitting/decommissioning. Access on: Oct. 24, 2020.

ANEEL (2020a). Sistema de Informações Geográficas do Setor Elétrico – SIGEL. Avaiable at: https://sigel.aneel.gov.br/portal/home/. Access on: Sep. 11, 2020.

ANEEL (2020b). Sistema de Informações de Geração da ANEEL-SIGA. Avaiable at: https://www.aneel.gov.br/siga. Access on: Jul. 10, 2020.

ANEEL. Resolução Normativa n° 876, de 10 de março de 2020. Estabelece os requisitos e procedimentos necessários à obtenção de outorga de autorização para exploração e à alteração da capacidade instalada de centrais geradoras Eólicas, Fotovoltaicas, Termelétricas e outras fontes alternativas e à comunicação de implantação de centrais geradoras com capacidade instalada reduzida. Brasília: Agência Nacional de Energia Elétrica – ANEEL. Available at: http://www2.aneel.gov.br/cedoc/ren2020876.pdf. Access on: Sep. 10, 2020.

ANEEL. Resolution No. 74 of March 25, 1998. Brasília: Agência Nacional de Energia Elétrica – ANEEL. Available at: http://www2.aneel.gov.br/cedoc/res1998074.pdf. Access on: Sep. 21, 2020.

ANEEL. Resolução n° 278, de 28 de setembro de 1999. Autoriza, para fins de regularização, a Centrais Eólicas do Paraná Ltda. a estabelecer-se como Produtor Independente de Energia Elétrica, mediante a implantação da Usina Eólio-Elétrica de Palmas, no Município de Palmas, Estado do Paraná. Brasília: Agência Nacional de Energia Elétrica – ANEEL. Available at: http://www2.aneel.gov.br/cedoc/res1999278.pdf. Access on: 01 Dec. 2020.

ANEEL. Resolução Normativa nº 389, de 15 de dezembro de 2009. Estabelece os deveres, direitos e outras condições gerais aplicáveis às outorgas de autorizações a pessoas jurídicas, físicas ou empresas reunidas em consórcio interessadas em se estabelecerem como Produtores Independentes de Energia Elétrica ou Autoprodutores de Energia de Elétrica, tendo por objeto a implantação e/ou a exploração de central geradora de energia elétrica. Agência Nacional de Energia Elétrica – ANEEL. Available at: http://www2.aneel.gov.br/cedoc/ren2009389.pdf . Access on: Oct. 05, 2020.

ANEEL. Resolução Normativa nº 876, de 10 de março de 2020. Estabelece os requisitos e procedimentos necessários à obtenção de outorga de autorização para exploração e à alteração da capacidade instalada de centrais geradoras Eólicas, Fotovoltaicas, Termelétricas e outras fontes alternativas e à comunicação de implantação de centrais geradoras com capacidade instalada reduzida. Agência Nacional de Energia Elétrica – ANEEL. Available at: http://www2.aneel.gov.br/cedoc/ren2020876.pdf. Access on: Oct. 05, 2020.

BAAK, W. (2019). Techno-economic analysis of repowering potential in North Rhine-Westphalia, Germany. 2019. Thesis (Master of Sience with focus on wind farm management) - Department of Earth Sciences, Uppsala University, Gotland, 2019.

BOMGARDNER, M. M.; SCOTT, A. 2018. Recycling renewables. Can we close the loop on old batteries, wind turbines, and solar panels to keep valuable materials out of the trash? Chemical & Engineering News 96: 15, CEN [online]. Available at: https://cen.acs.org/energy/renewables/Recycling-renewables/96/i15. Access on: Nov. 25, 2020.

BONA, J. C., FERREIRA, J. C., DURAN, J. O. Analysis of scenarios for repowering wind farms in Brazil**,** Renewable and Sustainable Energy Reviews, V. 135, 2021, 110197 Avaiable at: http://www.sciencedirect.com/science/article/pii/S1364032120304871. Access on: Nov. 13, 2020.

BRAZIL. Lei nº 10.848 de 15 de março de 2004. Dispõe sobre a comercialização de energia elétrica, altera as Leis [...], e dá outras providências. Brasília, DF: Presidência da República, [2004]. Disponível em: http://www.planalto.gov.br/ccivil_03/_ato2004-2006/2004/lei/l10.848.htm. Access on: Oct. 4, 2020.

BRAZIL. Medida Provisória nº 998, de 1 de setembro de 2020. Altera a Lei nº 9.991, de 24 de julho de 2000 [...] e dá outras providências. Available at: http://www.planalto.gov.br/ccivil_03/_ato2019-2022/2020/Mpv/mpv998.htm. Access on: Nov. 24, 2020.

BRAZIL. Ministério de Minas e Energia. Portaria nº 481, de 26 de novembro de 2018. Diário Oficial da União: seção 1, Brasília, ed 228, p.152. Nov. 28, 2018.

BRAZIL. Ministério de Minas e Energia, Empresa de Pesquisa Energética. Plano Decenal de Expansão de Energia 2029. Brasília: MME/EPE, 2020. Available at:

https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/plano-decenal-de-expansao-de-energia-2029. Access on: Sep. 10, 2020.

BRAZIL. 2010. Lei nº 12.305, de 2 de agosto de 2010. Institui a Política Nacional de Resíduos Sólidos; altera a Lei no 9.605, de 12 de fevereiro de 1998; e dá outras providências.

CanWEA. Decommissioning/Repowering a Wind Farm. Canadian Wind Energy Association. Avaiable at:: https://canwea.ca/communities/decommissioningrepowering-wind-farm. Access on: Dec 12, 2020.

CCEE. Resultado Consolidado dos Leilões – July,2020. São Paulo: Available at: https://www.ccee.org.br. Access on: Aug. 10, 2020.

Contech Engineered Solutions 2020. Tensionless Pier Wind Turbine Foundation. Available at: https://www.conteches.com/wind. Access on: Nov. 14, 2020.

DNV GL. DNVGL-ST-0262: Lifetime extension of Wind turbines, edition 2016-03. Available at: https://www.dnvgl.com/power-renewables/download/dnvgl-st-0262-lifetime-extension-of-wind-turbines-2016-03. Access on: Jul. 9, 2020.

Eletrobras. Plano Anual do PROINFA - PAP2020. Rio de Janeiro, 2019.

Energy Economic Times. India Announces Repowering Police. Available at: https://energy.economictimes.indiatimes.com/news/renewable/india-announces-repowering-policy-for-wind-energy-projects/53619122. Access on: Dec. 15, 2020.

Energy Facts. Vestas wins repowering order for the Overgaard II wind Project. Available at: https://www.energyfacts.eu/vestas-wins-repowering-order-for-the-overgaard-ii-wind-project/.Acesso em: Nov. 22, 2020.

Energy Global. China's wind repowering market to boom. Available at: https://www.energyglobal.com/wind/17122019/chinas-wind-repowering-market-to-boom/ Acesso em: Dec. 19, 2020.

Energy Watch. The Netherlands approves Vattenfall's big repowering Project. Available at: https://energywatch.eu/EnergyNews/Renewables/article11747727.ece. Access on: Oct. 20, 2020.

EPE. Projetos eólicos nos leilões de energia. Rio de Janeiro, 2020. Available at: https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-468/NT_EPE-DEE-NT-017-2020-r0.pdf. Access on: Jun 10, 2020.

ESPÉCIE, M.A.; SALIBA, A.S.; MATTOS, A.D.M.; COELHO; C.M.; ALMEIDA, E.M.; SODRÉ, F.N.G.A.S.; MORAES, J.B.; DURÃO, J.V.; PINHEIRO, M.R.C.; MATOS, R.O.; GUIMARÃES, R.V.; GOMES, V.S.M. 2018. Avaliação de impacto ambiental em projetos eólicos no Brasil: uma análise a partir de estudos ambientais de empreendimentos vencedores nos leilões de energia. In: 4º Congresso Brasileiro de Avaliação de Impacto, Fortaleza, 2018. 7p.

GUERRERO, P. C.; MANCINI, S. D.; TOUBIA, C. M. 2011. Caracterização e reciclagem química via pirólise de resíduos da fabricação de pás eólicas. Holos Environment, v.11 n.2: 147-157.

IDAM Infra 2018. Theme Paper: Procurement of Wind Power. Wind Vision India 2035. IDAM Infrastructure Advisory. Available at: https://idaminfra.com/wp-content/uploads/2016/07/Procurement-of-Wind-Power.pdf. Access on: Nov. 10, 2020.

Institute for energy research 2019. The Cost of Decommissioning Wind Turbines is Huge. Available at: https://www.instituteforenergyresearch.org/renewable/wind/the-cost-of-decommissioning-wind-turbines-is-huge/. Access on: Nov. 24, 2020.

International Electrotechnical Commission - IEC. IEC 61400-1: Wind Turbines – Part 1: Design Requirements, 3ªedição, 2005.

IWEA – Irish Wind Energy Association. Lifecycle of an Onshore Wind Farm. IONIC Consulting. 2019. Available at: https://www.iwea.com/images/files/iwea-onshore-wind-farm-report.pdf. Access on: Dec. 18, 2020.

JORGENSEN, B. H., HOLTTINEN, H., OPERANTING, I. W., DAHLGAARD, K., JAKOBSEN, K., & MARTÍ I. IEA Wind TCP Annual Report 2019. IEA Wind. 2019.

Kallista Energy. Le démantèlement et le renouvellement (repowering) de parcs éoliens. Available at: https://www.kallistaenergy.com/energies-renouvelables/demantelement-renouvellement/. Access on: Dec. 12, 2020.

KNUTSON, K. 2019. Wind farm repowering and decommissioning is big business. Energy Central. Available at: https://energycentral.com/c/cp/wind-farm-repowering-and-decommissioning-big-business. Access on: Nov. 25, 2020.

LANTZ, E., LEVENTHAL, M., & BARING-GOULD, I. (2013). Wind Power Project Repowering: financial Feasibility, decision Drivers, and Supply Chain Effects. Denver: NREL.

LARSEN, K. 2011. 2011. Recycling wind blades. Environment. National Wind Watch. Available at: https://www.wind-watch.org/documents/recycling-wind-blades/ .Acess on: Nov. 27, 2020.

LEAF, C. 2019. Wind farms: Why decommissioning must form part of the plan. Environment Journal. Avaiable at: https://environmentjournal.online/articles/wind-farms-why-decommissioning-must-form-part-of-the-plan/. Access on: Nov. 24, 2020.

LEÃO, R. P. S.; ANTUNES F. L. M., e FROTA, E. F. As Perspectivas da Energia Eólica no Estado do Ceará [1999]. Available at: http://www.abenge.org.br/cobenge/arquivos/20/st/t/t163.pdf. Access on: Sep. 21, 2020.

MARTÍNEZ, E.; LATORRE-BIEL, J.I.; JIMÉNEZ, E.; SANZ, F.; BLANCO, J. 2018. Life cycle assessment of a wind farm repowering process. Renewable and Sustainable Energy Reviews 93 (2018) 260–271.

ORNELLAS, L. F. T.; TOFANELI, L. A.; SOUZA, M. L. & e ALMEIDA, A. P. S. M. Descomissionamento de parque eólico no conceito da economia circular. BWP 2020.

ORNELLAS, L. F., TOFANELI, L. A., & SANTOS, A. Á. Aspectos do Gerenciamento da etapa de encerramento do contrato de geração de energia eólica no Brasil, com enfoque na Bahia. Em I. Winkler, L. L. Guarieiro, J. D. Barbosa, A. Á. Santos, J. P. Anjos, K. K. Amparo, & I. S. Figueiredo. Ciência, Tecnologia e Inovação: Desafio para um mundo Global. Ponta Grossa: Atena Editora, 2019.

RTPI - Royal Town Planning Institute. Why time-limited planning permissions on wind farms need to be rethought. : https://www.rtpi.org.uk/blog/2020/december/why-time-limited-planning-permissions-on-wind-farms-need-to-be-rethought/. Access on: Nov. 17, 2020.

Saur Energy. Can Repowering Deliver 10 GW of Wind Energy for India? Avaiable at: https://www.saurenergy.com/solar-energy-news/can-repowering-deliver-10-gw-of-wind-energy-for-india. Access on: Nov. 17, 2020.

SCHREINER, G. H.; CODONHO, M.L.P.C.F. 2018. Descomissionamento Ambiental: análise da temática em empreendimentos de geração de energia eólica. In: Jornada de Integração Científica, 4ª, 2018, Florianópolis. Cadernos de Iniciação Científica: Faculdade Cesusc, 2018, v.3, n.1.

Setterwalls. Repowering Wind Farms in Sweden – Securing Technical and Economical Sustainability. Available at: https://setterwalls.se/aktuellt/artikel/repowering-wind-farms-sweden-securing-technical-and-economical-sustainability-0. Access on: Nov. 28, 2020.

SIMÕES, T., S., COUTO, A., ESTANQUEIRO, A. Contribuição da repotenciação de centrais eólicas para as metas do PNEC 2030. LNEG – Laboratório Nacional de Engenharia e Geologia. Manutenção Eólica. Jul. 2019.

STAFFELL, I; GREEN, R. 2014. How does wind farm performance decline with age? Renewable Energy, v. 66, 775-786. Available at: https://doi.org/10.1016/j.renene.2013.10.041. Access on: Nov. 20, 2020.

TEREZA, J. C. 2019. Levantamento de opinião sobre o descomissionamento de parques eólicos no Brasil. Trabalho de Conclusão de Curso de Graduação em Engenharia de Energia - Universidade Federal de Santa Catarina. 44p.

The Portugal News. €18 million allocated to replace wind turbines in Vila do Bispo. Available at: https://www.theportugalnews.com/news/18-million-allocated-to-replace-wind-turbines-in-vila-do-bispo/47551. Access on: Dec. 15, 2020.

WISER, R.; BOLINGER, M. 2019. 2018 Wind Technologies Market Report. Lawrence Berkeley National Laboratory. U.S. Department of Energy (D.O.E.).

Wind Europe. Decommissioning of Onshore Wind Turbines-Industry Guidance Document. 2020. Available at: https://windeurope.org/data-and-analysis/product/decommissioning-of-onshore-wind-turbines/. Access on: Nov. 5, 2020.

Wind Europe. Repowering and Lifetime Extension: making the most of Europe´s wind energy resource. The European Wind Industry´s views on managing wind energy assets at end of their operational lifetime. 2017.

Wind Europe. Wind Energy in Europe: Outlook to 2023. 2019.

Windfair - The Wind Energy Portal. ACCIONA Finishes Repowering Project in Spain. Available at: https://w3.windfair.net/wind-energy/news/30492-acciona-nordex-turbines. Access on: Nov. 8, 2020.

WISER, R. H., e BOLINGER, M. Benchmarking Anticipated Wind Project Lifetimes: Results from a Survey of U.S. Wind. Lawrence Berkeley National Laboratory. 2019. Available at: https://eta-publications.lbl.gov/sites/default/files/opex_paper_final.pdf. Access on: Jul. 10, 2020.

Wood Mackenzie. 65GW of European onshore wind turbines need upgrades or replacements by 2028. Available at: https://www.woodmac.com/press-releases/65GW-European-onshore-wind-turbines-need-upgrades-or-replacements-by-2028. Access on: Dec. 10, 2020.

ZIEGLER, L., GONZALES, E., RUBERT, T., SMOLKA, U., & MELERO, J. J. Lifetime extension of onshore wind turbines: A review covering Germany. Renewable and Sustainable Energy Reviews, p. 11, 2018. Available at: http://dx.doi.org/10.1016/j.rser.2017.09.100. Access on: Jul. 20, 2020.

ZIMMERMANN, T. & GÖBLING-REISEMANN, S. 2012. Influence of site specific parameters on environmental performance of wind energy converters. Energy Procedia 20: 402 – 413.

APPENDIX

Data used in Item 4.2.1.

Table 3 - Capacity Factor Rates – Northeast and South

Capacity Factor Rate

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
NORTHEAST COAST (Average Capacity Factor = 32.0%)												
2012	103%	101%	94%	95%	98%	98%	124%	144%	146%	153%	103%	114%
2013	98%	127%	96%	55%	71%	69%	87%	129%	144%	139%	133%	106%
2014	112%	88%	72%	53%	58%	98%	114%	138%	138%	151%	114%	115%
2015	115%	84%	66%	51%	82%	87%	112%	143%	139%	140%	106%	107%
2016	52%	85%	78%	90%	79%	93%	120%	134%	145%	145%	133%	113%
2017	102%	78%	50%	64%	59%	83%	97%	110%	148%	132%	103%	94%
2018	80%	47%	45%	45%	59%	84%	105%	114%	133%	110%	124%	86%
2019	91%	49%	40%	36%	56%	88%	87%	130%	138%	135%	116%	107%
SOUTH (Average Capacity Factor = 29.0%)												
2012	96%	69%	81%	90%	81%	68%	90%	126%	144%	133%	102%	94%
2013	95%	73%	84%	103%	71%	78%	61%	98%	101%	126%	166%	118%
2014	68%	91%	85%	98%	68%	110%	115%	103%	137%	127%	104%	94%
2015	68%	79%	90%	72%	92%	67%	77%	127%	97%	140%	141%	100%
2016	113%	82%	92%	100%	83%	95%	116%	86%	115%	180%	116%	100%
2017	85%	72%	98%	123%	118%	86%	92%	127%	126%	133%	105%	131%
2018	105%	83%	62%	56%	94%	82%	101%	128%	127%	119%	150%	101%
2019	95%	63%	88%	65%	77%	67%	97%	99%	104%	100%	145%	120%

Table 4 - Energy Rates – Northeast and South

Capacity Factor Rate

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
NORTHEAST COAST (Average Energy = 361 W/m^2)												
2012	107%	97%	90%	97%	109%	109%	133%	195%	162%	176%	113%	118%
2013	104%	118%	95%	61%	84%	79%	99%	155%	155%	150%	138%	107%
2014	108%	87%	68%	52%	56%	93%	116%	155%	134%	149%	114%	107%
2015	100%	75%	53%	45%	73%	77%	92%	152%	130%	134%	100%	95%
2016	42%	67%	65%	74%	71%	94%	130%	136%	153%	142%	134%	96%
2017	87%	67%	42%	52%	59%	85%	117%	135%	174%	143%	117%	92%
2018	73%	40%	42%	39%	60%	89%	115%	125%	144%	111%	118%	74%
2019	68%	38%	26%	31%	54%	86%	79%	132%	134%	131%	106%	95%
SOUTH (Average Energy = 374 W/m^2)												
2012	106%	62%	77%	83%	77%	67%	87%	150%	197%	175%	137%	106%
2013	89%	67%	83%	97%	60%	76%	69%	85%	97%	141%	217%	112%
2014	63%	99%	70%	89%	57%	112%	104%	114%	153%	165%	116%	90%
2015	61%	64%	76%	65%	81%	51%	74%	119%	97%	165%	142%	100%
2016	115%	73%	85%	85%	67%	78%	155%	68%	142%	220%	104%	103%
2017	71%	65%	80%	125%	148%	78%	80%	164%	143%	142%	110%	123%
2018	91%	65%	45%	45%	81%	73%	99%	132%	125%	110%	157%	83%
2019	89%	49%	73%	52%	62%	51%	100%	85%	99%	97%	159%	113%