

Management of Waste from Post-Consumer Wind Power Farms in the Brazilian Scenario

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ABSTRACT

After the water crisis, Brazil implemented several policies with the aim of encouraging the search for new energy sources. Among them, wind energy has experienced accelerated growth in the last decade, due to its renewable nature, low cost, low greenhouse gas emissions, in addition to playing an important role in achieving the country's sustainable development goals. However, it is important to highlight that wind energy also generates significant environmental impacts. By 2030, more than 50 wind farms will reach the 20-year mark of operation, approaching the end of the useful life of their equipment and resulting in an increase in the generation of solid waste from this sector. Given this perspective, this study aims to analyze the strategies adopted by entrepreneurs after the end of the useful life of this equipment. A narrative review was carried out based on research into scientific articles published in the last 10 years. Careful planning is essential to evaluate the strategies to be adopted at the end of the useful life, minimizing the generation of solid waste.

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Introduction

Wind energy has experienced accelerated growth in the last decade, due to its renewable nature, low cost, low greenhouse gas emissions, in addition to playing an important role in achieving the country's sustainable development goals.

According to the US Department of Energy (n.d.), wind energy has many advantages, including being a renewable and clean energy source [1]:

- **Clean, Sustainable and Abundant Energy:** Wind turbines harness energy from the wind using mechanical power to spin a generator and create electricity. Not only is wind an abundant and inexhaustible resource, but it also provides electricity without burning any fuel or polluting the air.
- **Cost-Effective:** Land-based, utility-scale wind turbines provide one of the lowest-priced energy sources available today. Furthermore, wind energy's cost competitiveness continues to improve with advances in the science and technology of wind energy.
- **Wind Power Benefits Local Communities:** Wind projects deliver an estimated \$2 billion in state and local tax payments and land-lease payments each year. Communities that develop wind energy can use the extra revenue to put towards school budgets, reduce the tax burden on homeowners, and address local infrastructure projects.
- **Wind Turbines Work in Different Settings:** Wind energy generation fits well in agricultural and multi-use working landscapes. Wind energy is easily integrated in rural or remote areas, such as farms and ranches or coastal and island

communities, where high-quality wind resources are often found.

- **The Price for Wind Energy Continues to Decrease as Technology Improves:** As technology improves, the cost of wind is dropping. A 2019 study found that the cost of onshore wind had dropped by 27% since 2013, and that trend is anticipated to continue. In fact, this is a trend that is widely common across the entire renewables industry. In 2021, renewables officially became the cheapest energy source on earth [2].

According to, despite their many advantages, wind farms do have some challenges [3]. Some of the most common challenges include:

- They can be unsightly. Some people believe that wind turbines are an eyesore, especially when they are built in rural areas.
- They can generate noise pollution. The blades of a wind turbine rotate at high speeds, creating a humming or whirring sound that can be disruptive to nearby residents.
- They can be dangerous to birds and bats. When wind turbine blades rotate, they can create a low-pressure zone that can suck birds and bats into the blades.
- Good sites for wind farms are frequently found in isolated areas, making it difficult and expensive to build the necessary infrastructure to connect the wind farm to the electricity grid.
- Not the most aesthetically appealing [2].
- Construction can cause local disturbances [2].

Investments made in advanced technologies in the quest for the transition of energy matrices imply the development of new generation processes, as well as new materials and devices used

for this purpose. However, such technologies carry with them some types of manufacturing or post-consumer waste, which if not treated properly can be as harmful to the environment as those traditionally used [4,5].

Objective

Given this perspective, this study aims to analyze the strategies adopted by entrepreneurs after the end of the useful life of this equipment.

Methodology

A narrative review was carried out based on research into scientific articles published in the last 10 years.

Results and Discussion

The global energy transition represents a challenge in terms of promoting economic and social development based on lower carbon emissions and greater participation of clean and renewable sources. By reaching the 200 gigawatt (GW) mark of centralized power, Brazil proves its leading role and is in tune with the energy transition. According to data from the National Electric Energy Agency (ANEEL), of the 200 GW achieved, 84.25% are from renewable sources and 15.75% from non-renewable sources (1% Nuclear). Currently, the three largest renewable sources that make up the Brazilian electricity matrix are hydroelectric (55%), wind (14.8%) and biomass (8.4%) and of the non-renewable sources, the largest are natural gas (9%), oil (4%) and coal (1.75%) (Figure 1). This year, the Agency has already released 2 GW for commercial operation and confirmed the new mark through its Generation Information System and the Generation Supply Expansion Monitoring Report [6].

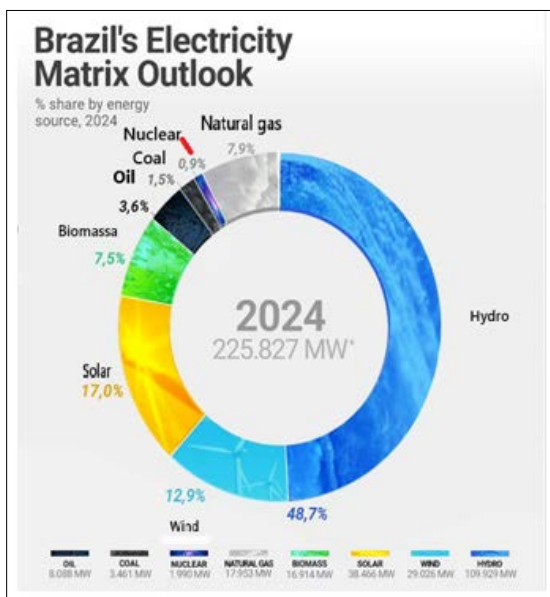


Figure 1: Brazil's Electricity Matrix Outlook [7].

A recent report published by the Global Wind Energy Council (GWEC) has highlighted Brazil's incredible rise as an emerging global wind power (Figure 2). In just 10 years, it has managed to reach sixth position in the world ranking, after moving up from fifteenth place. Brazil now has 21.5 gigawatts of installed capacity compared to 1 gigawatt in 2011, making wind energy the second largest contributor to the country's energy mix. However, China's leadership in wind energy, with 310 GW of installed wind capacity, is light years ahead of the rest [8].

During 2021, Brazil was also among Top 5 markets with the largest installed capacity, along with China, the United States, Vietnam and the United Kingdom. This was achieved by installing 3 GW of wind power capacity to reach the milestone of 20 GW of installed capacity during 2021, equivalent to 70% of the total capacity of the whole of Latin America (Figure 2).

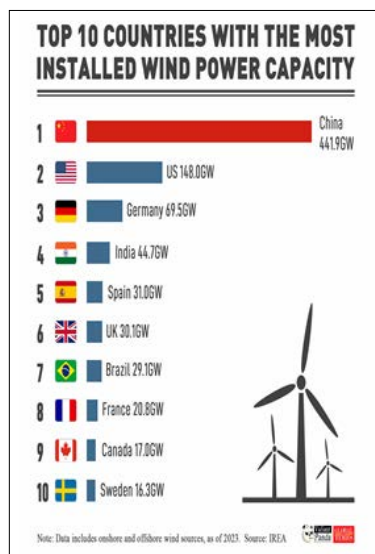


Figure 2: Top 10 Countries with the Most Installed Wind Power Capacity [9].

The first large-scale program to encourage the development of wind energy in Brazil was named PROEÓLICA. It started in 2001 as a government response to the energy crisis that the country was facing due to the reduced rainfall recorded and consequent low water storage in the reservoirs of national hydroelectric plants. Other government programs were subsequently implemented [10]. The success of wind power in Brazil can also be explained by the rapid development of an efficient local production chain [11].

After the water crisis, Brazil implemented several policies with the aim of encouraging the search for new energy sources. In recent years, Brazil's energy sector has faced significant challenges, mainly due to its dependence on hydroelectric sources. The 2021 water crisis was a turning point, exposing weaknesses in the energy generation and distribution system and raising long-term questions about the country's energy security. Even in 2024, the impacts of this crisis still resonate, and experts warn that 2025 may bring new challenges unless structural solutions are quickly and effectively implemented [12].

Although Brazil has one of the largest capacities for renewable energy generation in the world, its dependence on hydroelectric plants makes it vulnerable to water crises. The prolonged drought of 2021, considered the most severe in nearly a century, drastically reduced reservoir levels at the main hydroelectric plants. As a result, the government was forced to activate thermoelectric plants, which are more expensive and polluting, driving up energy costs and increasing inflation. In 2024, although the rains have returned, experts remain concerned about the possibility of new crises in the coming years. According to climatologists' forecasts, the El Niño weather phenomenon, which can cause severe droughts in some regions, could once again impact Brazil in 2025, putting additional pressure on reservoir levels. This possibility makes the energy crisis not just a memory of the past but a real threat on the horizon [12].

It is important to highlight that wind energy also generates significant environmental impacts. The manufacture stage is energy-intensive and is associated with a range of chemical usage [13]. Waste generation and end-of-life (EoL) management of wind power systems (WPSs) have attracted increasing attention as the number of decommissioned wind turbines continues to increase [14]. By 2030, more than 50 wind farms in Brazil will reach the 20-year mark of operation, approaching the end of the useful life of their equipment and resulting in an increase in the generation of solid waste from this sector. Over 94% of wind turbines are recyclable, but 6%, which corresponds to the blades, have no recycling solutions actually [15].

Implementing effective strategies for material recycling of wind turbine components is a key factor for sustainable management. This involves separating and recycling materials like steel, copper, aluminium, composites and plastic. Efficient recycling demands proper dismantling, material separation, and tailored recycling methods, which are capable of handling diverse materials within wind turbines. Concrete, steel & iron and composite are the three main waste streams generated by discarded wind turbines [16].

The main components of a wind turbine include a foundation, a tower constructed from either steel or concrete, a nacelle primarily composed of steel and copper, and three blades made from composite materials [17]. Composite recycling of these components poses a significant challenge because it lacks specific recycling channels, making it one of the more problematic materials for sustainable disposal and reuse [18].

By 2050, billions of tons of blade waste are projected to be generated globally, with the US and Europe leading the way. While some blades are landfilled or incinerated, there's increasing interest in innovative recycling and reuse solutions. One of the main challenges the world is beginning to face is the generation of large-volume waste (wind turbine blades), which is expected to exceed 40 million tons by 2050 [10]. This is related to the end of the lifespan of wind turbine blades, understood as the termination of their safe operational period. Other forecasts estimate 400,000 tons of waste annually by 2030, followed by 800,000 tons per year by 2050 [15].

Two major developments are occurring in conventional wind power systems: First, the turbines are becoming larger, and second, there is a shift from land-based to offshore locations. Offshore sites offer very high wind exposure levels combined with relatively large areas for utilization, while often having more limited local environmental impacts. The same basic wind turbine concepts are used as for onshore installations. The main challenges concern foundations and supporting structures, which can be either fixed or floating and are broadly similar to those encountered in offshore oil and gas exploitation. However, the corrosive marine environment does impose additional requirements on the turbines themselves, including the blades and their attachments [19].

According to a survey by the Energy Research Company (2021), by 2030, 51 wind farms (UEE) in Brazil will have exceeded 20 years of operation. There are more than 600 wind turbines, totaling 940 MW of power, approaching the end of their useful lives. Some factors that are related to the useful life of equipment: Durability of specific components, climatic conditions, operational conditions and equipment wear [20].

This turbine concept is expected to remain as the major provider of wind power in the foreseeable future. However, turbine sizes are increasing, and installation offshore means that wind turbines will be exposed to more demanding environmental conditions. Many challenges are posed by the use of fiber composites in increasingly large blades and increasingly hostile environments. Among these are achieving adequate stiffness to prevent excessive blade deflection, preventing buckling failure, ensuring adequate fatigue life under variable wind loading combined with gravitational loading, and minimizing the occurrence and consequences of production defects [19].

Recycling, especially of wind turbine blades, is seen as one of the main challenges for the industry. From 2030 onwards, more than 600 wind turbines will be discarded in Brazil, and given the speed of growth of wind energy, it is necessary to opt for alternatives (Table 1), since the volume of blades removed will increase rapidly [21].

Table 1: Options of Alternatives and Time of Useful Life Variation.

Options	Time of useful life variation
Extension of the operational life of turbines (also called Rehabilitation or Retrofit)	5 to 10 years
Reuse of the turbines	
Energy recycling, chemical recycling or mechanical recycling	
Partial repowering	10 to 15 years
Total repowering	20 to 25 years
Decommissioning and total deactivation of the park	25 to 30 years
Mixed solutions or other uses (architecture or structural elements)	

Adapted from [20,21].

Wind farms may produce waste during the preventive and corrective maintenance process. The waste must be collected at the generation sites themselves and transported by licensed companies for final disposal in accordance with the waste classification (Table 2).

Table 2: Destination of Solid Waste Generated in Wind Farms.

Waste	Destiny
Electrical components	Industrial landfill
Mineral oil from transformers	Recyclers
Lubricating oil for mechanical aggregates	Recyclers and cogeneration
Cables, wires and leftover electrical materials	Recyclers

Source: [22].

The waste must be collected at the generation sites themselves and transported by licensed companies for final disposal in accordance with the waste classification.

Brazil demonstrates a robust and progressive trajectory in the field of renewable energy, reinforcing its role as a leader in the global energy transition. With policies and investments focused on expanding clean and sustainable sources, the country not only consolidates its prominent position, but also establishes an inspiring model for other countries to follow. The commitment to sustainability, combined with technological and financial innovations, places Brazil at the forefront of energy transformation, a crucial step towards a greener and more sustainable future [23,24].

Conclusion

Regarding the waste generated by wind farms, there is still no consensus on the best practices for its use. Each project is unique, as is its regulatory and commercial context. Careful planning is essential to evaluate the strategies to be adopted at the end of the useful life, minimizing the generation of solid waste. In this scenario, much still needs to be studied in order to find suitable solutions to treat wind energy waste as a way of reducing negative impacts on the environment.

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