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GREENHOUSE GAS AND ENERGY PAYBACK TIMES OF A WIND TURBINE INSTALLED IN THE BRAZILIAN NORTHEAST

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Abstract. *This study applies the Life Cycle Assessment methodology to a wind turbine and verifies its environmental and energy payback times. The Life Cycle Assessment was developed with the SimaPro software, using the Ecoinvent database and the IPCC 2013 GWP 100y environmental impact assessment method. The Life Cycle Assessment considered the extraction of raw material, production of parts and pieces, transportation, assembly, use and decommissioning. Besides the material composition of the wind turbine, meteorological data was also utilized to calculate the production of energy at Patos (semi-arid region of the state of Paraíba, Northeast Brazil). The results of the environmental analysis and data on energy production were utilized to verify how long does the system have to operate to recover the energy—and associated greenhouse gas emissions - that went into making the system. It is demonstrated that the wind turbine has the potential to mitigate greenhouse gas emissions during its lifetime and that the energy and greenhouse gas payback times are under one year. The results obtained herein highlight the importance of combining Life Cycle Assessments with energy production calculations.*

Keywords: *Wind energy, environmental impacts, greenhouse gases, carbon footprint, life cycle assessment.*

1. INTRODUCTION

The generation of electricity to supply human demands has always been one of the priorities of modern society. However, the utilization of natural resources to meet these energy demands has not been carried out sustainably throughout the years (Dupont et al., 2015). As new energy conversion and supply technologies are developed, better use of resources and higher efficiency in electricity generation can be achieved.

In Brazil, annual National Energy Balances (NEB) are published with data referring to consumption and generation of electricity, from different sources. According to the 2019 report (NEB, 2019), there was a decrease of 5.5% in the share of electricity produced by thermal plants in comparison with the previous year. The contribution of renewable energy sources increased by 3.4%, which results in a 45.3% share of renewables within the national electricity matrix. Wind energy presented 14.4% increase in domestic supply when comparing 2018 and 2019 (NEB, 2019), which is a benefit to the environment, as it can displace the production of electricity from other sources with higher environmental loads.

Wind energy can be employed in low carbon schemes and to decarbonize electricity supply, such as in the case of Thailand, which aims to reduce greenhouse gas (GHG) emissions by 2021 with the help of wind energy (Sutabutr, 2012). Even though wind turbines not generate pollutants during operation, there are significant impacts on the environment during the production phase (manufacture of parts), construction and decommissioning (Uddin and Kumar, 2014). Also, wind turbines could influence the local microclimate (Azevedo et al., 2017).

One of the ways to reduce these environmental impacts is knowing the components required for the manufacture and construction of wind turbines, as well as formulating an action plan for final disposal, once the lifetime is over. This knowledge can assist in the selection of materials and methods that decrease overall impacts. In this context, the Life Cycle Assessment (LCA) methodology can be employed, which quantifies the environmental impacts and liabilities of a product, process or activity (Guezuraga et al., 2012).

Numerous studies have been developed to verify the environmental impacts caused by wind turbines in different locations (Uddin and Kumar, 2014; Oebels and Pacca, 2013; Al-Behadili and El-Osta, 2015; Guezuraga et al., 2012; Vargas et al., 2015; Tremeac and Meunier, 2009; Crawford, 2009; Wang and Teah, 2017; Schreiber et al., 2019). Different turbine configurations and different results were obtained, but the general conclusion was that there are significant environmental impacts embedded in the construction (and manufacturing) phase of the parts and decommissioning.

The objective of the study presented herein is to develop a LCA to quantify the greenhouse gas emissions associated with a wind turbine, calculate its energy production with meteorological data and technical parameters, and obtain the energy and GHG payback times. These metrics are the two most widely used environmental indicators to evaluate the sustainability and environmental performance of renewable energy systems.

2. MATERIALS AND METHODS

LCA is a consolidated, validated methodology for the quantification of potential environmental impacts associated with a product (process, or activity) throughout its life cycle (HAUSCHILD et al., 2018). An LCA can encompass the extraction of raw materials, manufacture, processing, distribution, transportation, use, maintenance, and final disposal. LCA is standardized by the International Organization for Standardization (ISO 14040, 2006; ISO 14044, 2006) and consists of four main phases: definition of the objective and scope (definition of the functional unit – to which all inputs and outputs are related to –, its life cycle, and system boundaries), inventory analysis (list of material and energy flows associated with the functional unit), impact assessment (selection of environmental impact assessment method to quantify environmental loads), and interpretation. LCA is often used by industries to improve processes, increase efficiency and reduce costs.

The LCA was developed herein with the SimaPro software 9.0.0.49 (Simapro, 2019), with the Ecoinvent database version 3.5 (2019) and environmental impact assessment method IPCC 2013 GWP 100y (IPCC - Full Report, 2013) that groups GHG emissions in a common metric, expressed in kg CO_2-eq, in a horizon of 100 years.

The wind turbine analyzed herein is a Gamesa onshore wind turbine, G8X model, with 2-MW rated power, and general dimensions: 80 m rotor blade, 5,027 m^2 sweep area (GAMESA, 2011). The wind turbine is considered to be installed in the city of Patos, Northeast Brazil. The environmental analysis encompassed the production of each component, transportation to the installation site, installation, start-up, maintenance and final decommissioning, with disposal of waste. Table 1 shows the material composition of the wind turbine, and the energy consumed in each phase.

Table 1. Wind turbine inventory.

Component	Sub-component	Mass	Material	Energy
Rotor	Three Blades	19.5 t	11.7 t resin 7.8 t fiberglass	20.15 MWh
	Blade Hub	14 t	14 t cast iron	12.00 MWh
	Nose Cone	0.310 t	0.124 t fiberglass 0.186 t resin	0.95 MWh
Foundation	Footing	725 t	700 t concrete 25 t iron	0.40 MWh
	Ferrule	15 t	15 t steel	4.72 MWh
Tower	Three Sections	143 t	143 t steel	47.22 MWh
Nacelle	Bed Frame	10.5 t	10.5 t iron	9.00 MWh
	Main Shaft	6.1 t	6.1 t steel	5.30 MWh
	Transformer	5t	0.149 t silica 1.5 t copper 3.3 t steel	55.56 MWh
	Generator	6.5 t	0.195 t silica 2 t copper 4.29 t steel	73.61 MWh
	Gear box	16 t	8 t iron 8 t steel	137.5 MWh
	Nacelle Cover	2 t	0.8 t fiberglass 1.2 t resin	6.20 MWh

Source: Martínez *et al.* (2009).

Regarding transportation, for the foundation, no transportation was considered. For the rotor, the tower and the nacelle, mean distances were considered for transportation by road: 700 km for the rotor, 810 km for the tower, and 2860 km for the nacelle.

For the final disposal of the wind turbine, it is considered that all iron is recycled (with 10% losses), fiberglass, PVC, other plastics, and rubber are landfilled, while steel and copper are recycled (with 10% and 5% losses, respectively). Removal of the foundation from the site would result in the use of heavy equipment and machinery, which could cause even more soil contamination and GHG emissions, and therefore it was considered that the foundation is left behind, covered with 30 centimeters of organic soil.

Mean wind speed data for the Patos location were obtained from its climatological station (period 1975-2014) (National Institute of Meteorology - NIMET, 2020). Wind speed data were acquired at a reference height of 10 meters, as established by Brazilian standards NBR 6123 (1990). It is therefore necessary to recalculate the approximate value of the wind speed for the height of the hub, according to Eq. (1) (Stiebler, 2008).

$$v_2(z_2) = v_1 \frac{ln\ (z_2/z_0)}{ln\ (z_1/z_0)} \tag{1}$$

where v_2 is the wind speed at height z_2, which is the height of the hub; v_1 is the average wind speed for that location; z_1 is the reference height, at which speed v_1 was measured; and z_0 is the length of the roughness, characteristic of each location. Herein z_2 = 80 m; z_0 = 0.5 m (Burton et al., 2001; Patel, 2006; Montero et al., 2018), and z_1 = 10 m. Table 2 shows the corrected mean wind speeds at 80 m height.

Table 2. Mean wind speed, in m/s, at 10 m height (1975 to 2014).

	Month											
	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Mean speed (m/s)	3,70	3,41	2,78	2,64	2,93	3,55	3,99	4,47	4,95	4,99	4,73	4,31

The power produced by the turbine is calculated according to Stiebler (2008):

$$P = c_p \frac{\rho}{2} A v_2^3 \tag{2}$$

where A is the area of the rotor; ρ is the specific mass of the air; and c_p is the power coefficient. It was considered that c_p and ρ are 0.5 and 1.2 kg / m³, respectively, and A is 5,027 m².

The energy payback can be defined as the time that a system has to operate to generate the same amount of energy that was spent in its manufacture, assembly, installation and final disposal. The time required to reset this energy balance is calculated as:

$$EPBT = \frac{E_{used}}{E_{saved}} \tag{3}$$

where EPBT is the time, in years, for the energy payback (Energy Pay-Back Time); E_{used} is the energy used to manufacture the system; and E_{saved} is the energy generated by the system over a year.

In addition to the energy payback time, it is possible to calculate the time required for the system to mitigate the GHG emissions from the wind turbine production, the GHG payback time (GPBT):

$$GPBT = \frac{Emissions_{LCA}}{Annual\ Emissions_{avoided}} \tag{4}$$

$$Annual\ Emissions_{avoided} = Turbine\ Production\ (EF_{ee} - EF_{wind}) \tag{5}$$

$$EF_{wind} = \frac{Annual\ Emissions_{LCA}}{Turbine\ Production} \tag{6}$$

where $Emissions_{LCA}$ is the total GHG emissions for the manufacture, installation, operation and disposal of the wind turbine (obtained via LCA), and Annual $Emissions_{avoided}$ is the annual avoided value of GHG emissions, calculated as the difference between the emissions that would be generated by consuming this electricity from the grid and the GHG emissions from the turbine. EF_{ee} refers to the emission factor of the electricity consumed in the country (kg CO_2-eq / kWh), and EF_{wind} refers to the emission factor of the electricity generated by the wind turbine (kg CO_2-eq / kWh). Annual $Emissions_{LCA}$ is the value of $Emissions_{LCA}$ divided by the lifetime of the system, considered herein as 20 years (Wang and Teah, 2017).

For the consumption of electricity from the national electricity grid (EF), the methodology presented by Carvalho and Delgado (2017) was followed to calculate the GHG emissions associated with the consumption of 1 kWh of electricity from the electricity grid in Brazil in 2019. Data from the National Electric System Operator (NESO, 2020a) was obtained, and the first, fifteenth and thirtieth days of the month were used to calculate monthly mean values, leading to the mean annual composition of the electricity mix: hydroelectric 66.67%, natural gas 9.28%, wind 9.15%, sugarcane bagasse 8.25%, nuclear 2.79%, coal 1.62%, fuel oil 1.55% and solar 0.69%.

3. RESULTS AND DISCUSSION

Table 3 shows the result of the GHG emissions associated with each component of the wind turbine system, using the information of Tab. 1 and the disposal process considered for each component.

Table 3. GHG emissions per component.

GHG Emissions (t CO_2-eq)				
Component	Sub-component	Manufacture	Transportation	Disposal
Rotor	Three Blades	85.30	2.30	12.20
	Blade Hub	6.25		-21.50
	Nose Cone	1.36		0.194
Foundation	Footing	136.00	--	--
	Ferrule	34.70		--
Tower	Three Sections	81.70	10.50	-220.00
Nacelle	Bed Frame	4.68	9.62	-16.10
	Main Shaft	3.46		-9.37
	Transformer	12.30		-7.41
	Generator	16.30		-9.72
	Gear box	8.11		-24.60
	Nacelle Cover	10.30		1.124
Total		400.46	22.42	-295.18

The three blades, the footing, the bed frame and the three sections of the tower are the sub-components that present the highest GHG emissions.

Regarding the foundation, it is divided into two sub-components: the footing and the bed frame. The footing is constituted of 700 t of concrete and 25 t of iron. According to Gomes et al. (2019), concrete is a composition of mineral and chemical additives, water, and cement, and is responsible for a considerable amount of GHG emissions: approximately 4% of global GHG emissions can be attributed to cement, according to Andrew (2018). For the bed frame and three sections of the tower, constituted of steel, there are also significant embedded emissions as reported by the Brazil Steel Institute (2010): approximately 95% of the energy employed in its production originates from solid fuels (mainly coal).

Although the nacelle presented the longest distance for transportation, this component did not present the highest GHG emissions.

Regarding decommissioning, the positive values (blades, nose and cover) shown in Tab. 3 refer to the landfill process. The negative values refer to the recycling processes of sub-components, which although utilizes energy, avoids the production of new material.

Table 4 shows the corrected values of the mean wind speeds, using Eq. (1) and Tab. 2.

Table 4. Mean wind speed, in m/s, corrected to 80m height (1975 to 2014).

	Month											
	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Mean wind speed (m/s)	6.27	5.78	4.71	4.47	4.96	6.01	6.76	7.57	8.39	8.45	8.01	7.30

From the wind speed data presented in Tab. 4, and with Eq 2, the energy produced by the wind turbine is calculated. Table 5 shows the monthly and annual mean wind turbine power. From December to May there is a reduction in wind speeds, consequently, a reduction in the power generated by the turbine.

From Tab. 5, the annual production of the wind turbine is 4198.59 MWh. Consideration of the energy consumed for the manufacture of the wind turbine (Tab. 1, 372.61 MWh) and Eq. (3) yields that EPBT = 0.08875 years, which is equivalent to approximately 34 days, or 0.47% of the wind turbine’s lifetime.

Table 5. Monthly and annual mean turbine power.

	Month												Annual
	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	mean
Power kW	371.4	290.8	157.6	134.9	184.5	328.1	465.8	654.9	889.4	911.1	776.0	587.1	479.3

Regarding the environmental payback, Annual $Emissions_{LCA}$ = 6,385 kg CO_2-eq/year. Thus, EF_{wind} = 0.001521 kg CO_2-eq/kWh. Following the methodology of Carvalho and Delgado (2017), the emission factor of electricity consumed from the Brazilian grid is 0.227 kg CO_2-eq/kWh. Thus, Eq. (5) provides $Emissions_{avoided}$ = 946,694.93 kg CO_2-eq over one year of operation. Finally, GPBT = 0.135 years, which is equivalent to 1 month and 18 days, approximately.

Comparing with existing studies, the order of magnitude of the paybacks is similar. Rankine et al. (2006) evaluated a type of wind turbine called SWIFT (1.5 kW and hug height 10 m). These authors evaluated different values of energy generated (1-2-3-4 MW) and obtained EPBT = 4.20-2.10-1.40-1.05 years and GPBT = 3.28-1.64-1.09-0.82 years. These times are much longer than those obtained herein, but the authors argue that microgeneration can be promoted to lower carbon emissions by replacing electricity from the grid with that produced by small generators in the home (fewer emissions associated with the construction and maintenance of a national electricity grid).

Marimuthu and Kirubakaran (2013) calculated the environmental and energy paybacks of a photovoltaic and wind systems in India. For the wind power system, EPBT = 1.12 years and GPBT = 50 days, considering a 1.65 MW turbine operating during one year. Haapala and Prempreeda (2014) analyzed two 2 MW wind turbines using LCA and EPBT, and obtained that environmental impacts were concentrated in the manufacturing stage, which accounts for 78% of impacts. EPBT were 5.2 and 6.4 months. Estimates for the GBPT of onshore wind ranged from six months to two years but construction on forested peatlands suggested this could approach six years, which is still lower than the average lifetime of wind systems (Thomson; Harrison, 2015a).

However, when expected decreases in grid emissions are taken into account, as mentioned by Thomson and Harrison (2015a; 2015b), longer payback times are expected, but should be achieved within the wind farm lifetime up to 2050. Wind farms constructed on the forested peatlands of Scotland after 2022 might not achieve payback, and research is required to verify how to minimize GHG emissions associated with construction at these locations.

The avoided emissions achieved by the operation of wind energy systems are usually obtained by comparing with fossil fuel-generated power plants (which could result in an overestimation) or with the electricity mix supplied by the national electric grid. However, wind actually displaces only the generators operating on the margin. Thomson et al. (2017) presented a methodology to isolate the marginal emissions displacement of wind power from historical empirical data, taking into account the impact on the operating efficiency of the conventional power plants operating in the UK. It was verified that wind power was almost as technically effective as demand-side reductions at decreasing GHG emissions from power generation.

Kaldellis and Apostolou (2017) reviewed studies published since 2000 and verified that most present EPBT under one year, for onshore and offshore wind farms. Offshore facilities usually present lower EPBTs, mainly due to higher wind speeds that enable higher generation (kWh/year). Dammeier et al. (2019) showed that the GPBT of wind turbines in northwestern Europe varied between 1.8 and 22.5 months.

LCA was emphasized by Stavridou et al. (2020) as crucial when assessing the real contribution of wind energy systems to environmental protection, with the most important parameters being EPBT and GPBT. Two tall onshore wind turbine towers were investigated, a lattice tower and a tubular tower, with EPBT of 4 and 5-6 months, respectively. GHG emissions could be further reduced by saving material from the foundation and tower, which are the most energy-consuming components of the wind structure. The authors confirmed that the most impactful stage in the lifetime of a wind turbine was the manufacturing phase, which was the same conclusion reached by Gomaa et al. (2019).

Comparing the EPBT and GPBT results obtained herein with those presented in scientific literature, most are under one year. Differences in values could be due to different wind speeds, electricity matrix of the country where the turbine is installed, methods used in the analysis, and individual characteristics of the turbines. It must be highlighted that all aforementioned studies considered a 20-year lifetime.

When placing the results obtained herein within a wider context, Fig. 1 shows the installed capacity (MW) of wind electricity generation, in Brazil and Northeast Brazil, for 2018 and 2019. It is observed that Northeast Brazil holds the majority of installed capacity, with increasing penetration, which demonstrates that the country is moving towards compliance with the Paris Agreement and to the diversification of the electricity matrix, consequently reducing the levels of GHG emissions.

The environmental benefits of introducing renewable energy generation in the electricity mix has already been shown for Brazil regarding solar photovoltaic electricity (Carvalho; Delgado, 2017) – and wind electricity has the potential to realize further benefits. Considering several wind farms and systems installed across Northeast Brazil, as shown in Tab. 6, with data obtained from Bracier (2020), Brennand Energia (2020), CPFL Renováveis (2012), Diário do Nordeste (2009), Echoenergia (2020), Engie (2020), Mangue Seco 2 (2020), Multiner (2020), Omega Energia

(2020), PacificHydro (2020), Neoenergia (2020), Paranoá Energia (2019), Renova Energia (2020), Statkraft (2020), Steag (2020) and The Wind Power (2020), the amount of avoided emissions is expressive and directly proportional to the installed capacity of the energy system, if used the turbine analyzed in this work.

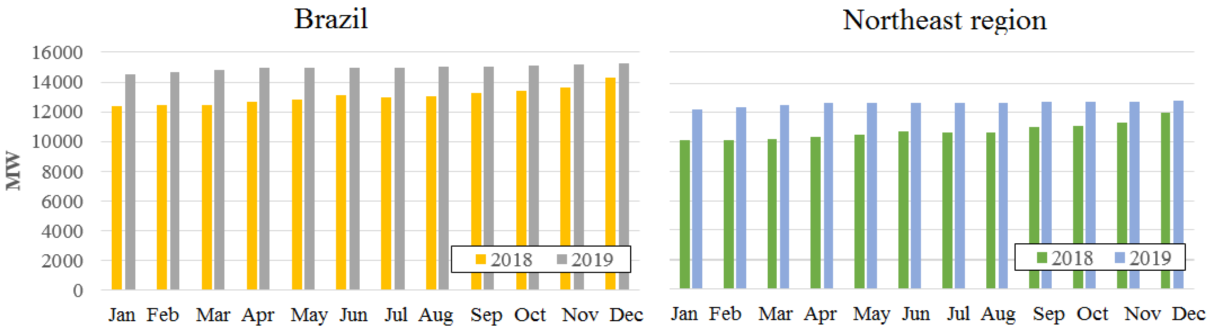

Figure 1. Installed capacity (MW) of wind power generation in Brazil and the Northeast region (NESO, 2020b). Available from www.ons.org.br/Paginas/resultados-da-operacao/historico-da-operacao.

Table 6. Data on wind farms located in Northeast Brazil.

Wind farm/complex	Installed Capacity [MW]	State	Emissions$_{avoided}$ [t CO_2-eq/year]
Delta Maranhão	426.00	Maranhão	201,646.02
Alto Sertão I	386.10	Bahia	182,759.46
Alto Sertão II	294.40	Bahia	139,353.49
União dos Ventos	234.70	Rio Grande do Norte	111,094.65
Ventos de São Clemente	216.00	Pernambuco	102,243.05
Santa Clara	188.00	Rio Grande do Norte	88,989.32
Alegria	151.80	Rio Grande do Norte	71,854.15
Morro dos Ventos	145.20	Rio grande do Norte	68,730.05
Ventos de Tianguá	130.00	Ceará	61,535.17
Echo 2	128.00	Rio Grande do Norte	60,588.48
Praia Formosa	104.40	Ceará	49,417.48
Bons Ventos da Serra II	86.10	Ceará	40,755.22
Echo 4	85.00	Rio Grande do Norte	40,234.53
Rio do Fogo	49.30	Rio Grande do Norte	23,336.03
Vale dos Ventos	48.00	Paraíba	22,720.68
Barra dos Coqueiros	34.50	Sergipe	16,330.49
Baraúnas I	32.90	Bahia	15,573.13
Morro Branco I	32.90	Bahia	15,573.13
Mussambê	32.90	Bahia	15,573.13
Banda de Couro	32.90	Bahia	15,573.13
Mundaú	30.00	Ceará	14,200.42
Fleixeiras I	30.00	Ceará	14,200.42
Guajirú	30.00	Ceará	14,200.42
Pedra Branca	30.00	Bahia	14,200.42
Sete Gameleiras	30.00	Bahia	14,200.42
São Pedro do Lago	30.00	Bahia	14,200.42
Estrela	29.00	Ceará	13,727.08
Ouro Verde	29.00	Ceará	13,727.08
Mangue Seco 2	26.00	Rio Grande do Norte	12,307.03
Baraúnas II	25.85	Bahia	12,236.03
Trairi	25.00	Ceará	11,833.69
Cacimbas	18.00	Ceará	8,520.25
Santa Mônica	18.00	Ceará	8,520.25
Millennium	10.20	Paraíba	4,828.14

From Tab. 6, the total amount of avoided emissions is approximately 1.491 Mt CO_2-eq/year. During the UN Climate Change Convention in 2015, Brazil voluntarily committed to reduce carbon emissions and in 2019 was within the established target of reducing by 36-39% the total emissions of the country (Brazilian Ministry of Environment, 2019). The implementation of renewable energy schemes has a strong influence on this reduction.

According to the Brazilian Business Council for Sustainable Development (BBCSD, 2019), the 2015 Paris Agreement established that the signatory countries were committed to reducing global warming, which is accomplished directly through the actions implemented by each country. Of the 38 participating companies, 21 are Brazilian or have information on the levels of emissions in Brazil (BBCSD, 2019) – this evidences a clear understanding that the improvement of services and actions have a direct impact on the environment, and electricity generation is one of the main areas that has a major influence on this factor.

Regarding the GHG emissions associated with thermal generators in standby for backup, it was considered herein that all energy generation technologies (e.g., coal, gas, nuclear, wind, solar) must be supported by other generators, with similar backup requirements. Therefore, the associated GHG emissions are minimal (National Renewable Energy Laboratory, 2013; Brooer et al., 2018).

Wind electricity, characterized by a lower amount of embedded energy and higher conversion efficiency, is becoming increasingly popular in recent years. At the same time, different options of energy conversion and supply systems are being developed, which motivates further research on the energy payback and environmental performances of each technology. The primary energy requirements (which lead to EPBT) and GBPT can vary from case to case due to different influencing factors, such as wind turbine model, manufacture process and technology, installation methods and locations, and climate parameters. Finally, it was demonstrated herein that wind electricity can be a sustainable and environmentally-friendly option, due to the EPBT and GPBT obtained.

4. CONCLUSION

The environmental performance of wind electricity is usually determined by a Life Cycle Assessment (LCA), and the environmental impact depends on the amount and type of materials and energy employed to build and maintain the wind turbine as well as the electricity produced over its lifetime. This study employed two widely-used environmental indicators, energy payback time (EPBT) and greenhouse gas payback time (GPBT) to assess the sustainability and environmental performance of wind power systems. Environmental information was obtained from the development of a LCA.

Although the wind speeds utilized herein, due to the location selected, were far from optimal, the production of electricity by the wind energy system was sufficient to obtain low values for EPBT and GPBT, under one year. Comparison with existing scientific literature revealed that the values were similar to other studies.

In Brazil, there is increasing research on energy and environmental aspects associated with wind power, but a lack of studies that verify EPBT and GPBT. The growth experienced in wind power generation is significant, which raises expectations for more work and research in this area. This study has demonstrated that wind electricity has the potential to mitigate climate change, and can be used in strategies to reduce environmental impacts.

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