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Evaluation of a Vertical Axis Wind Turbine for Use in Rural Areas

Rosemar Cristiane Dal Ponte[1], Enerdan Fernando Dal Ponte[1], Carlos Eduardo Camargo Nogueira[1], Jair Antonio Cruz Siqueira[1] & Divair Christ[1]

[1] Universidade Estadual do Oeste do Paraná, Cascavel, Paraná, Brazil

Correspondence: Rosemar Cristiane Dal Ponte, Universidade Estadual do Oeste do Paraná, Rua Universitária, 2069, Jardim Universitário, Cascavel, Paraná, CEP: 85.819-110, Brazil. Tel: 55-45-3220-7404. E-mail: rosemardalponte@hotmail.com

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Abstract

With the constant increase in the need for electricity, the use of wind energy emerges as an alternative that is capable of meeting these demands. Considering that several regions in Brazil have a great potential for wind power, it is necessary to develop technologies and investments to ensure the growth of this energy source. The purpose of this project was to study the technical and economic feasibility of a vertical axis wind turbine, which employed a washing machine motor, a servomotor and an alternator for electricity generation, in order to verify which generation system presents better efficiency. Additionally, the unit costs of the energy produced in each generation system were determined and compared to the value of the electricity tariff charged by the concessionaire for rural consumers. Based on the collected data relating to voltages and electric currents, the power and the wind-mechanical, mechanical-electrical and wind-electrical efficiencies of each generator system were calculated, allowing a comparison between these values. The alternator presented the best wind-mechanical efficiency (5.02%) and the best wind-electrical efficiency (0.47%). The washing machine motor showed the best mechanical-electrical efficiency (11.33%). The results showed that the systems have little efficiency in the generation of electricity, and the cost of energy generated indicates values much higher than those practiced by the local electricity concessionaire.

Keywords: wind energy, generation systems, efficiency

1. Introduction

With increasing demand for electricity and the scarcity of fossil fuel resources, renewable energy sources represent an alternative to meet these demands. Renewable energy sources include biomass, solar power, geothermal power, hydropower, and wind power. As a source of renewable energy, wind energy stands out due its features as a low-cost resource (Pinto, 2014).

Considering that several rural properties in Brazil are located far from the electricity transmission and distribution networks, the development and use of wind turbines appears as a promising route for the generation of electricity, thereby contributing to the social and economic inclusion in rural communities (Simas & Pacas, 2013).

Wind energy is a way of obtaining renewable, clean source energy that emits no greenhouse gases. It presents advantages such as reduced time of construction of the wind farm, possibility of use of the land for other purposes (agriculture and livestock), ease of expansion, and use in hybrid systems (solar-wind), among others (Gomes & Henkes, 2015).

According to Aldabó (2002), the energy of the winds that can be transformed into electricity is very low, reaching a maximum of 59.3% of the total energy (Betz's coefficient).

According to ANEEL (2016), Brazil is privileged in terms of the availability of renewable natural resources for energy use, including water resources, biomass, photovoltaics and wind power, in addition to being one of the countries with a higher percentage of wind power in its energy matrix.

Taking into consideration several regions of the country with great wind potential, the development of technologies and investments is essential to guarantee the growth of this energy source, it being necessary to establish means to facilitate the implementation of wind systems in a significant way, to achieve the maximum efficiency of the use and transfer of energy from the wind.

The use of wind energy in the regulatory market began in 2009, through the diversification of the electricity matrix and the priority contracting of renewable sources. Contributing to the insertion of this technology in the Brazilian market, wind farms amounted to 50% of the contracted electricity generation, with increasingly competitive energy prices, very close to the average values of conventional thermal power plants (Simas & Pacas, 2013).

The use of vertical axis wind turbines may present advantages, as they have a lower starting speed and can be positioned at lower heights, thereby reducing installation costs and facilitating the maintenance of the electric generator. In addition, they can be safer when used in stronger winds, requiring no additional wind tracking devices, unlike horizontal axis wind turbines (Svendsen & Merz, 2013).

The main purpose of this work is to evaluate the technical and economic feasibility of deploying a vertical axis wind turbine using different generation systems used in rural areas.

2. Material and Methods

The present study was developed in the Metalworking laboratory of SENAI (National Service for Industrial Training), Cascavel unit, state of Paraná (Brazil), with geographic location defined by coordinates 24°58′ S latitude and 53º26′ W Longitude and an average altitude of 781 meters above sea level.

A vertical axis wind turbine developed by Dal Ponte (2017) was used to analyze and compare the electricity generation efficiency, with a mass of approximately 20.70 kg, according to Figure 1.

Figure 1. Vertical axis wind turbine

Source: Dal Ponte, 2017.

The vertical axis turbine developed was based on the H-Darrieus model, consisting of blades, frame, bearings and a main shaft, with the following external dimensions: 2000 mm in diameter per 1000 mm in height.

Figure 2 shows the coupling of the wind turbine to the washing machine motor, servomotor and automotive alternator, composed of pulleys and belts. This set has a transformation ratio that totals a magnification of 10.8 times.

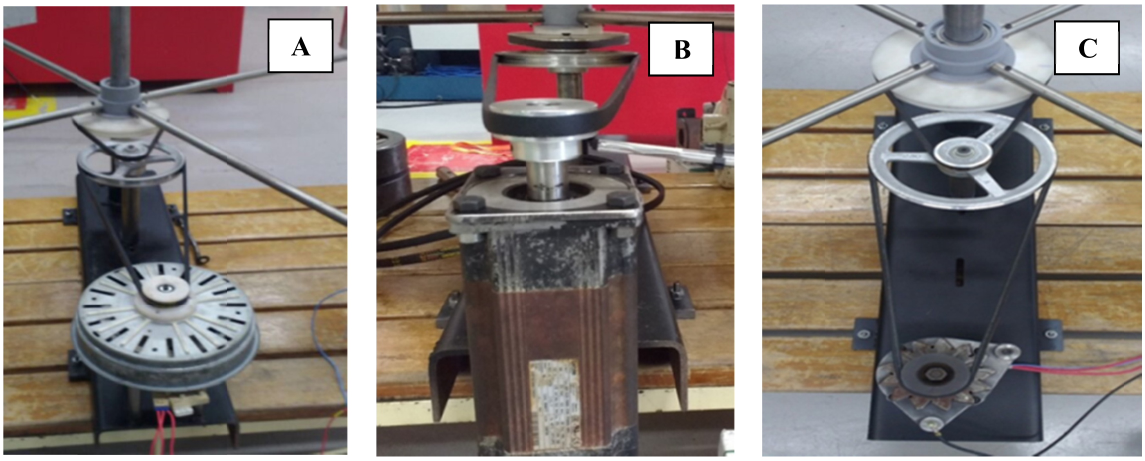

Figure 2. Motor rotation magnification assembly

Note. (A) washing machine motor coupling; (B) servomotor coupling; (C) automotive alternator coupling.

For the proposed development, the motors (operating as generators) were used according to the specifications below:

(a) Washing machine motor (alternating current with permanent magnets and rectifier), Electrolux brand, DON1300WN/ST model—three-phase, with a maximum power of 1,350 watts, maximum voltage of 127 V, and a maximum rotation of 1400 rpm;

(b) Servomotor (alternating current), Lenze brand, MCS12L20 model—three-phase, with maximum power of 2.8 kW, maximum voltage of 330 V, and a maximum rotation of 1,950 rpm;

(c) Automotive alternator (alternating current), Bosch brand, with power of 540 W, and voltage of 12 V.

The tests were carried out for each generator under study, using an axial fan, with dimensions of 700 mm in diameter and 400 mm in depth, with a three-phase motor of 7.5 hp and 220 V, controlled by a frequency inverter of the WEG brand, CFW 08 model, with the aim of increasing wind speed, to put the turbine in motion.

To avoid wind dispersion and try to approach the tests of real field situations by directing the air, a wind tunnel was built and the wind turbine was positioned in its interior.

For each generator, the following data were collected: wind speed using a thermo-anemometer of the Instrutherm TAFR-180 model; generator shaft rotation using a digital tachometer of the Minipa MDT-2244B model; the force exerted by the turbine blades with the aid of a digital dynamometer of the Instrutherm DD-500 model; voltage and alternating current, with the aid of multimeters of the Tenma 72-6870 model and pliers ammeters of the Minipa ET- 3990 model.

In order to verify the behavior of the electricity generation in different load variations, a resistor bank was dimensioned, totaling 25 W of theoretical maximum load, connected in parallel, ad in order to vary the load, the resistors were fractionated into 10 kΩ , 5 kΩ, 3.33 kΩ, 2.5 kΩ, 2 kΩ.

The wind speed, generator shaft rotation, force exerted by the turbine, voltage and alternating current were initially collected for a no-load system. For each step, the stipulated time was 3 minutes. Subsequently, a switch was turned on, triggering a load of 10 kΩ. The same procedure was performed for the loads of 5 kΩ, 3.33 kΩ, 2.5 kΩ, and 2 kΩ, a time of 18 minutes being added.

The positioning of the motors and measuring equipment used can be seen in Figures 3a and 3b.

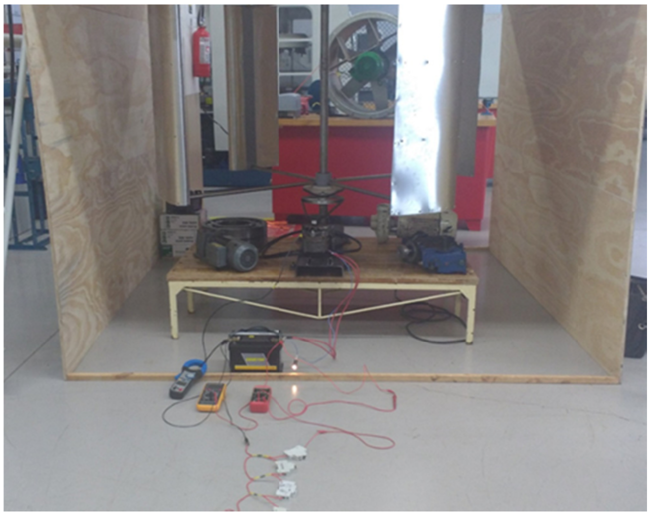

Figure 3a. Positioning of measuring instruments

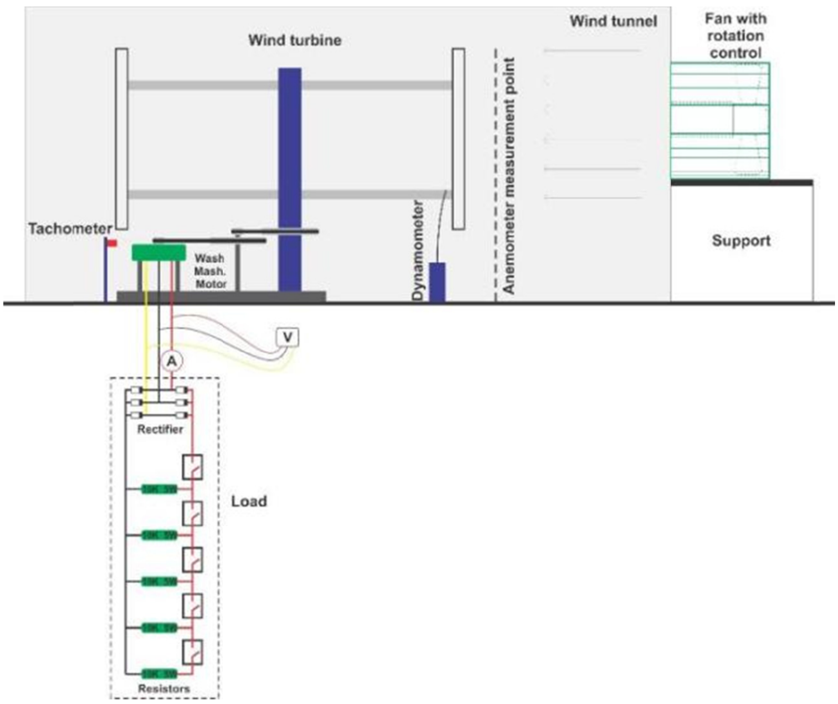

Figure 3b. Generation system assembly

Based on the data collected, the wind power, mechanical power, electrical power and efficiency of each system were calculated, in accordance with the following equations:

$$\text{Wind Power (W)} = \tfrac{1}{2}\rho A v^3 \rho \tag{1}$$

$$\text{Mechanical Power (W)} = [\text{Torque (Nm)} \times \text{Shaft rpm}]/9.555 \tag{2}$$

$$\text{Electrical Generation Power (W)} = \text{Voltage (V)} \times \text{Current (A)} \tag{3}$$

$$\text{Wind-Mechanical Efficiency (\%)} = [\text{Mechanical Power (W)}]/[\text{Wind Power (W)}] \times 100\% \tag{4}$$

$$\text{Mechanical-Electrical Efficiency (\%)} = [\text{Mechanical Power (W)}]/[\text{Wind Power (W)}] \times 100\% \tag{5}$$

$$\text{Wind-Electrical Efficiency (\%)} = [\text{Electrical Generation Power (W)}]/[\text{Wind Power (W)}] \times 100\% \tag{6}$$

$$\text{Energy (Wh)} = [\text{Power (W)} \times \text{Measurement time interval (min)}]/60 \tag{7}$$

Wind power was calculated with a mean wind speed of 12.84 m/s, turbine area of 2 m^2 and air density of 1,225 kg/m^3, according to Equation 1.

The mechanical power was calculated according to the data collected from the value of the torque (Nm) and the turbine rotation for each generation system, according to Equation 2.

The calculation of the electrical power was based on the data collected from the voltage and the alternating current of the different generation systems, according to Equation 3.

For the purposes of cost comparison, a constant wind speed was considered throughout the year. Similar to the values stipulated in this experiment, with a wind turbine operating availability factor of 90% of total annual hours, resulting, therefore, in 7884 hours/year of effective power generation. In the remaining 10% (876 hours/year), it was considered that the wind turbine will be stopped for maintenance.

To calculate the annual energy generation in each system, the average power multiplied by the number of hours was used.

3. Results and Discussion

From the three replications for each generation system, each of 18 minutes duration, the average of the wind power generation systems was calculated, and the results are described in Tables 1, 2 and 3. In table 1, the data collected referring to the average of the tests performed with the washer motor.

Table 1. Data acquired from the means of the washing machine motor tests

Load	Vac (V)	Iac (A)	Generator rotation (rpm)	Turbine rotation (rpm)	Alternating power (W)
Open Circuit	44.00	0	164	15	0
10 kΩ	34.00	0.049	139	12	2.89
5 kΩ	33.10	0.048	126	1	1.75
3.33 kΩ	25.40	0.034	89	8	1.50
2.5 kΩ	20.40	0.029	85	7	1.02
2 kΩ	22.90	0.029	80	7	1.15

The data in Table 1 above show the variations in the added load; the mean of the alternating and average voltages of the alternating currents between the washing machine motor and the bridge rectifier; the mean rotations of the main shaft of the turbine, which was calculated based on the drive shaft rotations and the multiplication factor of the expansion assembly composed of pulleys; and the alternating power obtained by the multiplication between the voltage and the alternating current expressed in W.

According to the table above, it is possible to observe that as the load increases (that is, the resistance decreases), the power values also decrease. This fact occurs due to the technical characteristics of the generator and the load, considering that the motor of the washing machine presents limited generation potential in relation to the required load demand.

In Table 2 it is shows the data referring to the means of the tests performed with the servomotor.

Table 2. Data acquired from the means of the servomotor tests

Load	Vac (V)	Iac (A)	Generator rotation (rpm)	Turbine rotation (rpm)	Alternating power (W)
Open Circuit	152.30	0	641	59	0
10 kΩ	114.70	0.00012	537	49	0.02
5 kΩ	161.20	0.00568	174	16	1.59
3.33 kΩ	142.50	0.01465	165	15	3.62
2.5 kΩ	158.50	0.03029	156	14	8.32
2 kΩ	160.00	0.03016	151	13	8.36

According to the data presented in Table 2, as the load increases (*i.e.*, resistance decreases), the power values also increase. This occurs because of the technical characteristics of the generator and the load, considering that the servomotor has a higher generation potential than the one required by the load, thereby indicating that more load could be added and, subsequently, a higher generation could be obtained.

In Table 3 it is shown the data referring to the means of the tests performed with the automotive alternator.

Table 3. Data acquired from the means of the automotive alternator tests

Load	Idc (A)	Iac (V)	Generator rotation (rpm)	Turbine rotation (rpm)	Generator Power/Battery (w)
Open Circuit	0	12.58	981	90	0
10 kΩ	1.20	12.68	938	86	15.22
5 kΩ	1.10	12.67	940	87	13.94
3.33 kΩ	0.70	12.72	947	87	8.90
2.5 kΩ	0.90	12.75	945	87	11.48
2 kΩ	0.88	12.88	949	87	11.33

As presented in Table 3, as the load increases (*i.e.*, resistance decreases), the power values also decrease. Notwithstanding, when comparing the behavior of the alternator with the washing machine motor, it is observed that both presented limitations in relation to the load. It was verified that the alternator presented greater generation potential.

Table 4 presents the data on the electrical power generated in each system, considering the variation of resistive loads mounted in parallel.

Table 4. Generated electrical power

Load	Washing Machine Motor Power (W)	Servomotor Power (W)	Battery Power (W)/Alternator Load
Open Circuit	0	0	0
10 kΩ	2.89	0.02	15.22
5 kΩ	2.75	1.59	13.94
3.33 kΩ	1.50	3.62	8.90
2.5 kΩ	1.02	8.32	11.48
2 kΩ	1.15	8.36	11.33

In Figure 4 it is shown the comparison between the mean of the resistive load variations and the mean power (W) generated by the different systems. It is verified that the highest generated powers were obtained by the automotive alternator, using a resistive load of 10 kΩ, which generated 15.22 W. The lowest power generated by the alternator was of 8.90 W for a load of 3.33 kΩ.

The servomotor presented powers of 1.59 W and 8.36 W for loads of 5 kΩ and 2 kΩ.

The washing machine motor showed the lowest power among the systems analyzed, generating 2.89 W for a load of 10 kΩ and 1.02 W for a load of 2.5 kΩ.

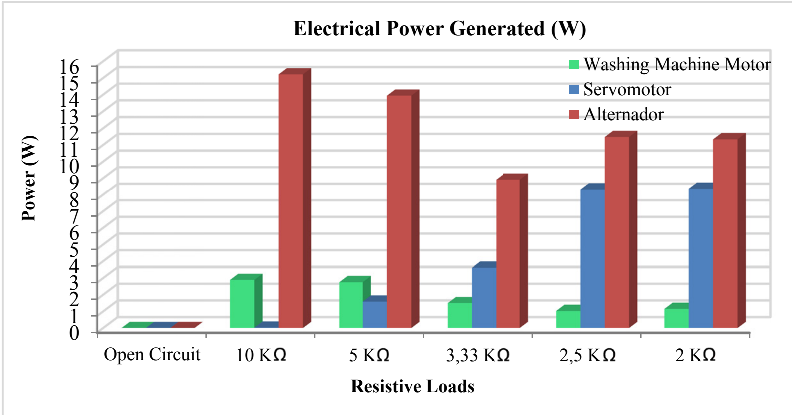

Figure 4. Electrical power generated

In Table 5 it is shown the data on the mechanical power available, generated in each system.

Table 5. Mechanical power available

Load	Washing Machine Motor			Servomotor			Alternator		
	Turbine Rotation (rpm)	Torque (Nm)	Mechanical Power (W)	Turbine Rotation (rpm)	Torque (Nm)	Mechanical Power (W)	Turbine Rotation (rpm)	Torque (Nm)	Mechanical Power (W)
Open Circuit	15	10.47	16.44	59	18.09	111.70	90	13.81	130.08

According to the table above, it is possible to verify the system that presented the highest mechanical power available, *i.e.*, the automotive alternator, which generated 130.08 W. The servomotor system presented a power of 111.70 W, while the washing machine motor had lower power, reaching 16.44 W.

The data on wind-mechanical efficiency obtained in the systems according to the variation of resistive loads mounted in parallel, in relation to a mean wind speed of 12.84 m/s, generating a wind power of 2593.17 W.

Through Figure 5, it is possible to establish a comparison between wind power and mechanical power, enabling the verification of the system that showed the best wind-mechanical efficiency percentage. The alternator was the most efficient with a percentage of 5.02%. In turn, the servomotor presented an efficiency of 4.31% and the washing machine motor presented a percentage of 0.63%.

As observed in Figure 5, independent of the loads used, the percentage of wind/mechanical efficiency remained constant.

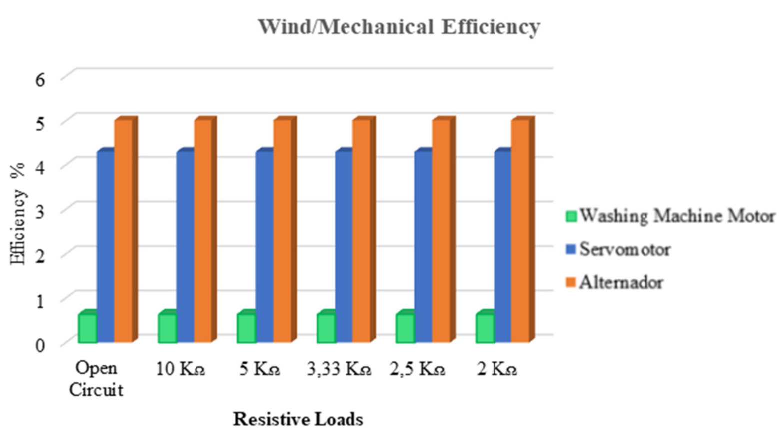

Figure 5. Wind-mechanical efficiency of the systems

In Figure 6, it is possible to verify which system presented the best mechanical-electrical efficiency percentage. The system that used the washing machine motor was the most of efficient for resistive loads of 10 kΩ, 5 kΩ, and 3.33 kΩ, with percentages of 17.56%, 16.74%, and 9.10% respectively.

The servomotor presented efficiencies of 7.48% and 7.44% for the loads of 2 kΩ and 2.5 kΩ. The alternator presented efficiencies of 11.70% for a resistance of 10 kΩ and 10.71% for 5 kΩ.

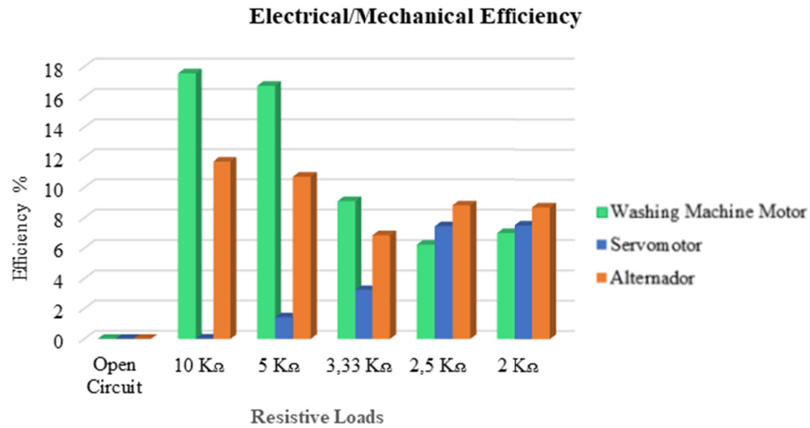

Figure 6. Mechanical-electrical efficiency of the systems

According to Figure 7, the generation system that used the servomotor obtained an efficiency percentage of 0.06% for a resistive load of 5 kΩ and 0.32% for a load of 2 kΩ. The system that used the automotive alternator obtained an efficiency percentage of 0.58% for a resistive load of 10 kΩ and 0.34% for 3.33 kΩ. The system that used the washing machine motor was the least productive, with the lowest efficiency percentage, reaching 0.11% for 10 kΩ and 0.04% for a load of 2.5 kΩ.

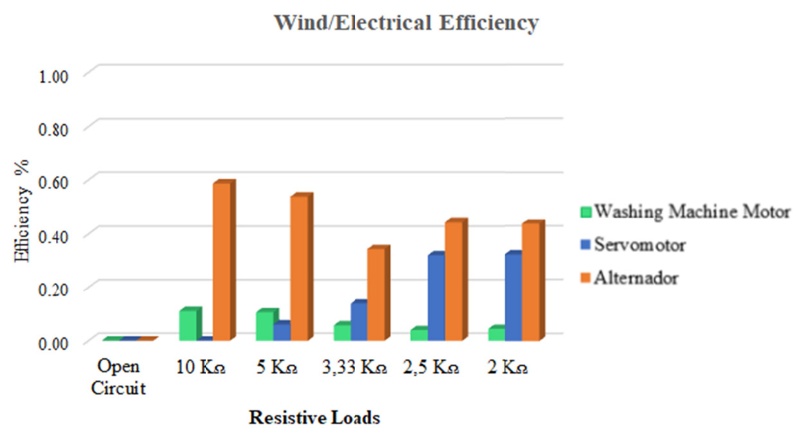

Figure 7. Wind-Electrical efficiency of the systems

In Table 6 it is shown the data referring to the mean efficiencies obtained in the different systems.

Table 6. Mean efficiency percentages

Motor	Wind/Mechanical Efficiency	Mechanical/Electrical Efficiency	Wind/Electrical Efficiency
Washing Machine Motor	0.63	11.33	0.07
Servomotor	4.31	3.92	0.17
Alternator	5.02	9.36	0.47

On Table 6, it can be observed that the system that used the automotive alternator was the one that obtained the highest mean wind-mechanical efficiency, reaching 5.02%, followed by the servomotor with 4.31% for this efficiency. The washing machine motor had the lowest wind-mechanical efficiency, reaching 0.63%. The system that used the washing machine motor showed the highest mechanical-electrical efficiency, at 11.33%, followed by the system that operated with the alternator, with 9.36%, and the servomotor, with 3.92%. For wind-electrical efficiencies, all systems presented low percentages, ranging from 0.07% to 0.47%.

In Table 7 it is shows the data referring to initial and maintenance costs for the installation of the different power generation systems.

Table 7. System costs

	Washing Machine Motor	Servomotor	Alternator
Initial cost of the system in R$ (turbine + motor)	2,263.07	2,462.57	1,776.07
Service life (years)	20	20	20
Maintenance cost p.a. in R$ (2% of the initial cost	45.26	49.25	35.22

Considering a 4-year automotive battery life according to the manufacturer's specifications, and considering 10% p.a. interest rate as benchmark of the financial market; the annual cost of the battery used in the generator system with the alternator was R$ 141.66.

Similarly, using an interest rate of 10% pa and a 20-year useful life, according to engine manufacturer specifications, the costs per year for the washer motor (R$ 311.06), the servomotor (R$ 338.48) and the automotive alternator (R$ 385.79).

Considering that the energy system is expected to operate 7884 hours/year, the calculations of the total energy per generator used are exemplified below:

Total Annual Washing Machine Energy = 1.86 × 7.884

Total Annual Washing Machine Energy = 14.6642 kWh/year

Total Annual Servomotor Energy = 4.38 × 7.884

Total Annual Servomotor Energy = 34.5319 kWh/year

Total Annual Alternator Energy = 12.17 × 7.884

Total Annual Alternator Energy = 95.9483 kWh/year

Table 8 presents data on annual investment costs, annual energy generated (kWh/year), and the cost of energy generated by the systems in R$/kWh.

Table 8. Costs vs. energy generated

System	Costs/Annual Investment (R$)	Annual energy generated (kWh)	Cost/Energy Generated (R$/kWh)
Washing Machine Motor	311.06	14.66	21.21
Servomotor	338.48	34.53	9.80
Alternator	385.79	95.95	4.02

In Table 8, it is possible to establish a comparison between the generated energy (kWh) and the energy cost generated in (R$/kWh) for each system. The automotive alternator generated an annual energy of 95.95 kWh, and the cost of energy was R$4.02/kWh. This system was the one that presented the best unit cost.

Compared with the data from the auctions held in December 2017, wind energy obtained a mean marketing price of R$0.19 per kWh. The costs of energy generated (R$/kWh) in the analyzed systems were higher than the final values practiced by the market (MME, 2017).

4. Conclusions

It was possible to verify in this work, the technical-economical feasibility of the implantation of a vertical axis wind turbine using different systems, for the generation of electric energy. The studied systems presented low efficiency indexes, due to the characteristics of the resistive loads used in the generation systems that were adapted, and of the wind turbine efficiency itself.

Through the analysis of the results obtained, it was verified that the automotive alternator was the system that presented the best wind mechanical efficiency (5.02%) and the best wind electric efficiency (0.47%). The motor of the washing machine, in turn, presented the best mechanical-electrical efficiency (11.33%).

The system that used the automotive alternator generated 95.95 kWh per year, costing R$ 4.02/kWh, which presented the best unit cost. Through the economic feasibility analysis, it was verified that the systems presented high energy costs generated, when compared to the electricity tariffs charged by Copel, whose value for the rural subgroup B2 is R$ 0.48/kWh plus taxes.

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